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NON-INTEGRATED GAS TURBINE ENGINE DIAGNOSTICS TRADEOFF ANALYSIS--ETC(U)
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U. S. NAVAL AIR ENGINEERING CENTER

LAKEHURST, NEW JERSEY

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NAEC-GSED-100 10 May 1977

CODE IDENT. NO. 28638

FINAL REPORT

NON-INTEGRATED GAS TURBINE ENGINE DIAGNOSTICS
TRADEOFF ANALYSIS

AIRTASK A3400000/051B/6F41461400 WU 11

DEPARTMENT OF THE NAVY ★ NAVAL AIR ENGINEERING CENTER ★

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I. SUMMARY

A. Diagnostic equipment and techniques to be included in a non-integrated system to detect and isolate the four most prevalent malfunctions in existing Navy aircraft gas turbine engines were selected.

B. Each of the diagnostic elements (techniques/methods/equipment) delineated in report NAEC-GSED-88, Survey on Current and Proposed Diagnostic Systems, and additional elements specified by NAVAIRENGCEN were evaluated. The technical capabilities of these elements were compared with the engine failure modes set forth in report NAEC-GSED-85, Analysis of Turbine Engine Failure Modes. A determination was made as to which elements best satisfy engine diagnostic requirements and indicate potential within the parameters of technical feasibility and cost effective application.

C. This study was generally applicable to all gas turbine engines utilized in Navy aircraft. Technical information was obtained by research of available technical literature, discussions with technical personnel of the U.S. Navy and U.S. Air Force directly involved with engine diagnostics, visits with operational personnel at each level of maintenance, consultations with recognized experts and solicitation of information from equipment manufacturers. Each area was pursued until it was assured that accurate information in sufficient quantity had been obtained to judiciously evaluate the merits of each designated technique, method and/or equipment. Technical information was sufficient for the purpose of the study, however, occasional proprietary limitations were encountered.

D. An Embryonic Non-Integrated Gas Turbine Engine Diagnostic System was developed. Those elements (techniques/methods/equipment) which qualified as meeting the standards of technical feasibility, cost effectiveness and satisfying engine diagnostic requirements were merged into a coordinated, functioning whole system. Each individual element was qualified as to function, capability and its relationship to overall system operation and logic. An engineering development plan was structured which quantifies and qualifies implementation of the elements into the non-integrated engine diagnostic system and presents milestones, initial development plans, development times and relationship of elements to system operation.

E. Gas path analysis, with trending, and borescope inspection were selected as the most effective methods to diagnose the leading engine malfunctions (63%), foreign object damage and hot section distress. Other elements to be included in the proposed embryonic system are oil analysis, time temperature recording indicator/low cycle fatigue counters, vibration testers, trim testers, test system vibration equipment, vibration signal analysis equipment, temperature sensing system testers, and Jetcal analyzers. Oil analysis techniques being developed indicate a significant improvement compared to spectrometric analysis for diagnostic

purposes. A summary of specific elements for utilization of each of three levels of maintenance and an engineering development plan with proposed implementation milestones are included.

II. PREFACE

A. This study was performed to correlate the results of previous analyses which identified the most prevalent failure modes of aircraft gas turbine engines with possible diagnostic elements in an effort to develop a non-integrated system which would enhance aircraft engine maintenance and detect impending engine malfunctions prior to in-flight catastrophic failure. Technical feasibility, cost-effectiveness and diagnostic needs were to be considered.

B. Increased emphasis has been directed toward engine diagnostics in the recent past due to the impact of increasing engine life cycle costs including initial cost, overhaul, maintenance and recurring costs, supply support and spare parts costs. A savings in the spare engines inventory, through increased engine life and availability, is possible with early detection and proper correction of malfunctions. There is a current and foreseeable shortage of skilled personnel both at sea and ashore at all levels of maintenance to contend with the support requirements demanded by the increasing complexity of engines.

C. Advances in technology have expanded the ability to develop an effective engine diagnostic system as a result of improved sensor capability, proliferation of miniaturized integrated circuits and the ready availability and unprecedented capacity of relatively small digital computers. The variety and frequency of planned engine related parameters being measured, averaged, recorded, analyzed, trended and stored has grown at an ever increasing rate. As a result, a variety of diagnostic elements (methods, techniques, equipment) have come into being, each of which was designed and developed to perform an individual and specialized function. Design and development efforts have not been thoroughly coordinated and an effective and functional diagnostic system is not yet available for use at the fleet level.

D. Naval Air Engineering Center report NAEC-GSED-85, Analysis of Gas Turbine Engine Failure Modes of October 1974, identified the prevalent failure modes and causes for engine removals. The results were obtained by analyses of applicable 3M data and manual review of maintenance records at U.S. Navy Intermediate and Depot repair activities over a six month period. Engine models included in the study were: J-52, J-79, T-56, T-58, TF-30 and TF-41; a total of 240 engines failures were documented. Removal of the engine from the aircraft in order to effect repair was a necessary condition to be classified a failure. An additional 50 engines removals which occurred during the same period were subsequently found to be non-failure and were categorized as false removals. The major causes of failures, from the 240 engine samples, were foreign object damage-33%, thermal stress-30%, internal oil leakage-9%, excessive vibration-4%, with the remaining 24% unclassified. It is the object of this study to judiciously select or trade diagnostic elements to detect and localize these four major failure modes.

E. The diagnostic elements to be considered are those presented in Naval Air Engineering Center report NAEC-GSED-88, Survey on Current and Proposed Diagnostic Systems, dated January 1975. Included in this report are fifteen methods or techniques, not all of which are applicable to a non-integrated system. Each applicable element has been addressed with respect to capability of achieving the desired objectives. An additional ten devices were selected to be included as potential diagnostic candidates.

F. The term non-integrated, as applied to engine diagnostic systems, connotates system/element is separate from the engine, system/element utilizes existing sensors or has adapters and sensors compatible with existing engines and system/element requires no extensive rework to existing engines or sensors.

G. The purpose of this study was essentially threefold:

1. Perform a diagnostic element tradeoff/selection analysis in order to:

a. Evaluate each of the diagnostic techniques, methods, and/or equipment discussed in the NAVAIRENGCEN Survey report and additional methods specified.

b. Compare the capabilities of each technique, method or equipment with the engine failure modes in the NAVAIRENGCEN Analysis report to determine which elements best satisfy engine diagnostic needs and requirements.

c. Determine which elements show the greatest promise from the standpoint of technical feasibility, cost-effectiveness and diagnostics need.

d. Recommend engineering development of those elements which best satisfy Navy needs.

2. Specify an initial or embryonic diagnostic system based on the recommended diagnostic elements.

3. Prepare an engineering development plan which is specifically designed to produce the specified system.

H. This study was completed during the period July 1975 through March 1976, with the assistance of Q.E.D. Systems, Inc., Virginia Beach, Va.

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VI. TRADEOFF ANALYSIS

A. BACKGROUND

1. This effort was performed to correlate the results of previous analyses which identified the most prevalent failure modes of aircraft gas turbine engines with possible diagnostic elements in an effort to develop a non-integrated system which would enhance aircraft engine maintenance and detect impending engine malfunctions prior to in-flight catastrophic failure. Technical feasibility, cost-effectiveness and diagnostic needs were considered. It has been estimated that a significant reduction of non-discrepant engine removals and early detection of foreign object damage and potential internal engine failures can be achieved through the application of selective state-of-the-art detection and diagnostic techniques.

2. Report NAEC-GSED-85, Analysis of Gas Turbine Engine Failure Models of October 1974, identified the prevalent failure modes and causes of engine removals. The results were obtained by analyses of 3M data and a manual review of maintenance records at U.S. Navy Intermediate and Depot Level repair activities over a six month period. Engine models included in the study were J-52, J-79, T-58, TF-30 and TF-41; a total of 240 engine failures were documented. Removal of the engine from the aircraft in order to effect repair was a necessary condition to be classified a failure. An additional 50 engine removals, which occurred during the same period were subsequently found to be non-failure and were categorized as false removals. The major causes of failures, from the 240 engines sampled, were foreign object damage-33%, thermal stress-30%, internal oil leakage-9%, excessive vibration-4%, with the remaining 24% unclassified. It is the objective of this study to judiciously select or trade diagnostic elements to detect and localize these four major failure modes.

3. The diagnostic elements to be considered are those presented in report NAEC-GSED-88, Survey on Current and Proposed Diagnostic Systems, dated January 1975. Included in this report are fifteen methods or techniques, not all of which are applicable to a non-integrated system. Each applicable element has been addressed with respect to capability of achieving the desired objective. An additional ten devices were selected by NAVAIRENGCEN to be included as potential diagnostic candidates.

4. The term non-integrated as applied to engine diagnostic systems connotates system/element is separate from the engine, system/element utilizes existing sensors or has adapters and sensors compatible with existing engines and system/element requires no extensive rework to existing engines or sensors.

B. STUDY SCOPE.

1. The purpose of this study was essentially threefold:

a. Perform a Diagnostic Element Tradeoff/Selection Analysis. Evaluate each of the diagnostic techniques, methods and/or equipments discussed in the NAVAIRENGCEN Survey report and additional methods specified by NAVAIRENGCEN. Compare the capabilities of each technique, method or equipment with the engine failure modes in the NAVAIRENGCEN Analysis report to determine which elements best satisfy engine diagnostic needs or requirements. Determine which elements show the greatest promise from the standpoint of technical feasibility, cost-effectiveness and diagnostics need. Recommend engineering development of those elements which best satisfy Navy need.

b. Specify an initial or embryonic diagnostic system based on the diagnostic elements recommended in paragraph a. above.

c. Prepare an engineering development plan which is specifically designed to produce the system specified in paragraph b. above.

2. This study was generally applicable to all gas turbine engines utilized in Naval Aircraft. Technical information was obtained by research of available technical literature, discussions with technical personnel of the U.S. Navy and U.S. Air Force directly involved with engine diagnostics, visits with operational personnel at each level of maintenance, consultations with recognized experts and solicitation of information from equipment manufacturers. Each area was pursued until it was assured that accurate information in sufficient quantity had been obtained to judiciously evaluate the merits of each designated technique, method and/or equipment. Technical information was sufficient for the purpose of the study, however, occasional proprietary limitations were encountered. This study was performed during the period July 1975 through March 1976.

C. PROCEDURES.

1. The initial phase of this study consisted of reviewing research material and various plausible concepts which could be correlated to the most frequently occurring malfunctions to be diagnosed. Each of the concepts had major limitations such as physical capability, excessive instrumentation and precision requirements, impractical for field application, retrofit restrictions, inordinate operator skill, inconclusive or insufficient test results and prohibitive cost. It was soon apparent that no single element or device was available with the possible exception of the borescope, which could consistently detect and localize the predominant malfunctions of foreign object damage and hot section distress. It was concluded that, for a viable non-integrated system, each element must have progressed sufficiently through the development

and test cycle that successful operational performance could be confidently expected in order to preclude excessive development time with questionable ultimate capability. Utilization of off-the-shelf, reliable hardware would increase the probability of acceptance, and provided other criteria are satisfied, enhance overall effectiveness and operational acceptance. It was also considered imperative that the system be intended for and economically attractive to current operational engines, particularly in view of the advances and enthusiams for integrated systems.

2. Validity of the most prevalent engine malfunctions was further substantiated by examining Naval Safety Center major aircraft accident records. Each engine caused major aircraft accident which involved J-52, J-79, TF-30 or TF-41 engines during a five period ending August 1975 was reviewed to identify specific failure causes for comparison with those engine malfunctions which were previously determined by reviewing maintenance data. A total of 53 accidents involving the selected engines were conclusively assigned engine failure as the primary cause. These accidents are categorized in Table I.

TABLE I

ENGINE CAUSED AIRCRAFT ACCIDENTS
FAILURE MODE

CAUSE	NUMBER	% OF TOTAL
Compressor Failure	12	23
Turbine Failure	10	19
Fuel Leak	8	15
Bearing Failure	7	13
Internal Oil Loss	4	7
Foreign Object Damage	3	6
Other	9	17

3. Percentage of each model engine involved in these accidents and relative percentage of engine population is presented in Table II.

TABLE II

ENGINE CAUSED AIRCRAFT ACCIDENTS
ENGINE MODEL

MODEL	ACCIDENT INVOLVEMENT - %	RELATIVE POPULATION - %
J-52	43	38
J-79	19	38
TF-30	28	16
TF-41	9	8

4. The data of Table I essentially substantiates the previously identified major engine malfunction causes determined from maintenance records. Although foreign object damage was not predominant, compressor

failure would in most cases be classified as FOD if detected during maintenance.

5. Table II should not be interpreted to indicate relative engine reliability because engine operating hours are not included, the engines were at different stages of maturity during the period and, most significantly, the data demonstrate the advantages of multi-engine installations. All Navy J-79 installations are multi-engine, whereas J-52 are both single and multi-engine. The TF-30 was predominantly single engine during this period, and TF-41 was exclusively single engine. It was also noted that 60% of J-79 engine related accidents were the results of fuel leaks and not directly an engine malfunction. The data of Table I provide additional economic justification for an effective diagnostic system and substantiate the validity of the selected engine malfunctions being considered for diagnosis. The data of Table II conclusively support the advisability of directing initial priority to engines utilized in single engine applications for any diagnostic system.

D. DIAGNOSTIC ELEMENTS.

1. Increased emphasis has been directed toward engine diagnostics in the recent past as a result of advancement in sensor capability, proliferation of miniaturized integrated circuits, higher potential cost savings and, most significantly, by ready availability and unprecendented capacity of relatively small digital computers. Consequently, the frequency and variety of planned engine and related parameters being measured, averaged, recorded, analyzed, trended and stored has grown at an ever increasing rate. The physical quantities which are indeed required and the optimum measurement technique in order to achieve the gas turbine engine diagnostic objectives are critically examined for each element/system included in this analysis.

2. The diagnostic elements which were to be considered during this study are presented in Table III. Column headings are the major malfunctions, determined by frequency of occurrence, which were to be diagnosed. The relative percentage of occurrence of each malfunction is also included in the column heading. Each element has been qualitatively classified for each malfunction with respect to capability to detect that a malfunction exists and identify the malfunction location. From this table, it is noted that among the potential non-integrated system elements, only the borescope provides conclusive detection and isolation of the two most prevalent malfunctions, foreign object damage and thermal distress. Other elements may indirectly infer an unknown number of malfunctions by indications such as overtemperature, mass unbalance, performance degradation or out of tolerance instrumentation, hwoever, additional examination is required to confirm the indication and localize the malfunction.

TABLE III

QUALITATIVE EVALUATION OF CANDIDATE ELEMENTS

ELEMENTS	FOD (33%)	THERMAL STRESS (30%)	INT OIL LEAK (9%)	EXCESS VIB (4%)
IEDDS *	X/X	X/X	X/O	X/X
IECMS **	⊕/⊕	⊕/⊕	⊕/O	X/X
VIB ANAL	⊕/⊕	⊕/⊕	O/O	X/X
SONIC ANAL	⊕/⊕	O/O	O/O	⊕/⊕
FLT DATA RCDR	+	+	+	+
TTRI	O/O	X/X	O/O	O/O
SOAP	O/O	O/O	O/O	O/⊕
BORESCOPE	X/X	X/X	O/O	⊕/⊕
HOLOGRAPHIC INSP	O	O	O	O
RADIOACTIVE TEMP IND	O/O	+	O	O
JET CAL	O/O	⊕/O	O/O	O/O
TRIM TEST	⊕/⊕	⊕/⊕	O/O	O/O
OPTICAL PYRO	O/O	⊕/⊕	O/O	O/O
THERMOGRAM	O/O	⊕/⊕	O/O	O/O
ENG VIB (TF-34)	⊕/⊕	⊕/⊕	O/O	X/X
ADDITIONS				
THRUST MEAS	⊕/O	⊕/O	O/O	O/O
T-56 TREND	⊕/O	⊕/O	O/O	O/O
GS 7800-147	O/O	⊕/O	O/O	O/O
UNIV VIB TEST	⊕/⊕	⊕/⊕	O/O	X/X
TRIM TEST (GE)	⊕/⊕	⊕/⊕	O/O	O/O
TRIM TEST (PW)	⊕/⊕	⊕/⊕	O/O	O/O
LASER VIB SENSOR	⊕/⊕	⊕/⊕	O/O	X/X
SHOCK PULSE	⊕/⊕	⊕/⊕	O/O	X/X
ELECTRO PROBE	O/O	O/O	O/O	O/O
GAS PATH ANALYSIS	⊕/⊕	⊕/⊕	O/O	O/O

* INTEGRATED ENGINE DIAGNOSTICS & DISPLAYS SYSTEM

** INFLIGHT ENGINE CONDITION MONITORING SYSTEM

DIAGNOSE / ISOLATE
X - YES
O - NO
⊕ - VARIABLE
\+ - REQUIRES ADDITIONAL EQUIPMENT

3. In view of the physical insufficiency of other elements of Table III to consistently detect either foreign object damage or thermal stress, it was concluded that other possible methods must be considered. For the purposes of this study, broad interpretations are applied to FOD and thermal stress, the former to include any structural damage to compressor blades, fan rotor, stators or inlet guide vanes regardless of the offending source. Similarly, thermal stress is interpreted to include any structural damage incurred by combustion chambers, turbine nozzles, turbine rotors or turbine discs which could be attributed to the effects of high temperature or a combination of applied stress and high temperature.

4. All devices which could be identified as possible diagnostic elements as the result of a thorough search of technical literature were considered as possible candidates. Included among the elements were millimeter wave interferometer, magnetic field technique, remnant magnetic field, ion probe, radiographic inspection, and internal accelerometers. Each was successively excluded for various reasons including ineffectiveness, insufficient or conflicting test results and unrealistic economic requirements.

E. EVALUATION OF EXCLUDED ELEMENTS. The following paragraphs contain a detailed description and evaluation of each element/system and justification for exclusion of the element/system from a non-integrated diagnostic system.

1. Shock Pulse Indicator.

a. This technique has been developed to measure the mechanical health of gears and bearings operating in rotating machinery. The method is related to vibration measurements in that an accelerometer is used as a sensor, however, signal processing and display is unique. The equipment consists of an accelerometer with 38 KHz resonant frequency, a high gain amplifier tuned to the accelerometer resonant frequency and a counter which displays the rate in pulses per second that displacements exceed any selectable desired value. The threshold displacement level is varied, the rate of occurrence noted at each level and the results graphically displayed as a plot of rate vs threshold level. The shape of the resulting curve is used to evaluate bearing or gear condition, with an increasing rate of occurrence at higher threshold displacement level generally indicating a mechanical defect or irregularity.

b. This technique has been utilized with helicopter gears and bearings and implanted defects have been detected. The helicopter drive train, external to the engine and readily accessible, was utilized for these tests. Similar to vibration measurements, for meaningful results the sensing accelerometer must be in close proximity to the rotating element under investigation, either bearings or gear. It has been estimated that signal attenuation in the range of 80% occurs across a mechanical interface. It is for this reason, as with bearing vibration measurements, that this technique is not considered applicable to the non-integrated diagnostic system. Merits of this technique compared to classical vibration methods have not been pursued.

c. There were several results from the shock pulse helicopter tests which could be extended to engine diagnostics. The shock pulse technique, in addition to exposing mechanical defects, is reported to indicate the presence of foreign matter in the lubricant. This is indicated by a high rate of low level shocks, amplitudes exceeding a particular threshold level. An observation during the test was that shock pulse data correlated directly if the damage originated in the bearings, however, if originating in the gears, the indication was obtained indirectly through the sensing of particulate contaminants passing through the bearings. It was also concluded that manual plotting of shock emission data and the judgment required to determine bearing health was not compatible with maintenance personnel. Since interpretation of vibration data is more complex than shock pulse results, this conclusion in conjunction with the contaminated lubricant observation further substantiates the desirability of developing an oil analysis technique with sufficient reliability to conclusively detect gear and bearing defects.

2. Electrostatic Probe.

a. The concept of the electrostatic probe technique originated in November 1970 during testing conducted by the Air Force Flight Dynamics Laboratory. The technique involves monitoring the release of engine material into the gas flow predicated on the assumption that a primary process involved in many gas path failures is the loss of material during hot section burn erosion and during rub of rotating stages. Detecting material loss was to be effected by placing a simple electrode in the engine exhaust which could detect particles via charge transfer between particles and the electrode or by some other mechanism associated with particle-to-probe collision. A simple electronic circuit would be used to count the number of particles and thereby indicate particle emission level in the gas path.

In addition to the USAF, investigators included Mt. Auburn Research Associates, Detroit Diesel Allison Division, General Electric Co., Pratt and Whitney Aircraft, United Aircraft Research Laboratories, National Aeronautics and Space Administration Lewis Research Center and Federal Aviation Administration National Aviation Facilities Experimental Center. Experiments were conducted using a variety of gas turbine engines and laboratory devices. Included among methods to simulate failure were injecting metal particles, deflecting the turbine seal into the rotating blade tips to cause rub and inserting steel rods into the combustion chamber. Numerous hours of piggyback testing were conducted in addition to over 6000 hours on a non-interference basis using TF-41, T-56, F101, TF-39, TF-34, TF-30, J-52, JT-9D and other engines. Although there was not agreement throughout the conclusions of all investigators, a general inability to reliably correlate engine distress with probe signals was apparent. In the NASA tests, stainless steel rods were inserted into the combustion flame and allowed to burn. A water-cooled electrostatic probe, placed in a position downstream best suited for particle impact, recorded only noise counts identified as due to a ringing test cell telephone and electric motor noise. Testing at NASA Lewis Research Center was suspended in March 1974 due to unprogressive results and higher priority programs. A joint USAF/FAA effort used four J-60 turbojet engines as test articles. The results were again unsuccessful. In one test, a steel rod was driven directly into the rotor which generated visible emission of particle sparks from the engine burner, however, numerous attempts to detect particles were unsuccessful. This effort was officially terminated in June 1974. It appears that any success with the electrostatic probe method did not extend beyond coincidence.

b. Air Force Aero-Propulsion Laboratory Technical Report TR-74-96 dated March 1975 was a Final Report for the period of June 1972 - June 1974 which included a comprehensive summary and evaluation of the electrostatic probe technique to detect turbine engine gas path distress. The first conclusion of this report was, "The electrostatic probe technique for a detection of particles emitted during distress of turbine engine gas path components has not been demonstrated to have the effectiveness and reliability necessary for advanced development or application in the foreseeable future". In view of the preponderance of evidence that the electrostatic probe technique is not capable of consistently detecting engine distress, it is not considered further in this study.

3. Radioactive Temperature Indicator (RTI).

a. Direct measurement of temperature within the turbine inlet and combustion areas of gas turbine engines is not feasible because thermocouple probes exposed to the gas stream in these areas would be rapidly eroded by impingement of high temperature gases. One of several ingenious methods to measure temperatures in these areas is the Radioactive Temperature Indicator. The Radioactive Temperature Indicator measures gas density. The theory of operation is based on the phenomenon that the number of electrons absorbed in a gas stream is a function of density. An electron emitter is directed across a gas stream with counting effected on the opposite side by an electron detector. Electron count is then correlated to indicate gas density. A corresponding and accurate pressure measurement is also required which, with density, is inserted into an Equation of State to compute temperature. Temperature measurement accuracies within 1% have been reported using this method. The temperature measured is the average through the path between emitter and detector. This path length is limited because electron intensity varies inversely with distance squared.

b. Accurate gas temperature measurements in the combustion or turbine nozzle area would be useful in gas path analysis. Knowing the difficulty in measuring extreme temperatures, the requirement for this parameter was avoided in the J-52 gas path analysis example in this report. Except as an input to gas path analysis, measurement of this temperature is not sufficiently applicable to the non-integrated diagnostic system to warrant the complexity involved. If gas path analysis is applied as a diagnostic system to other engines, the requirement to know combustion chamber temperature would have to be evaluated for each individual engine. In most cases, the temperature is determined indirectly through measurement of compressor discharge and turbine exit total temperatures. Utilization of an electron emitter or other complex system for temperature measurement is considered appropriate during engine development to evaluate combustor performance or determine temperature profiles. Minimum complexity is essential for any successful operational engine diagnostic system in order to realize a reliable, useful and maintainable system and thereby instill operator confidence and acceptance. In the case of the J-52, it was shown that measurement of extreme temperature was not required to obtain meaningful results from gas path analysis. Similar methods should be applicable to other engines or the temperature can be determined indirectly. This latter method of measuring temperature or any other parameter used for gas path analysis does not degrade the results because criteria are based on change in performance and the absolute value is not significant.

c. As an indicator of temperature exceedances, measurement of turbine out temperature provides the required data for a steady state diagnostic system. Individual thermocouple readings should be trended as an indication of combustion irregularities resulting from fuel nozzle discrepancies or other abnormalities in fuel or air distribution. The advisability of continuously monitoring exhaust gas temperature to evaluate cumulative deterioration is included in the discussion of Time Temperature Recording Indicator.

4. Jet Engine Fuel Control Performance Analyzer Model GS7800-147.

a. This analyzer was developed to measure installed fuel control performance. The analyzer is physically separated into two cases, one containing the control assembly panel, X-Y recorder/plotter and three signal conditioning modules and the other holds attaching cables, transducers and adapters. The analyzer measures transient and steady state values of engine RPM, compressor or turbine discharge pressure and fuel flow. These data are processed and combined for subsequent display by the X-Y plotter as the ratio of fuel flow to burner pressure as a function of engine RPM. The shape of the resulting curve is used to identify fuel control malfunctions.

b. This analyzer has disadvantages which preclude its further consideration as a candidate element in a non-integrated diagnostic system. The most serious discrepancy is that innumerable malfunctions associated with the engine, other than the fuel control, would be indicated by an abnormal curve shape. As an example, during testing at the Naval Air Test Center, an X-Y plot deviated from known good engine/fuel control plots thus indicating a fuel control malfunction. The real cause of the indicated malfunction was subsequently revealed as a damaged hydraulic fuel pump. It is conceivable that a library of curves could be constructed which would identify specific malfunctions as a function of curve shape. Preparation of a complete set of curves to depict all possible malfunctions would require a major effort and extensive test time in addition to continual updating to reflect relevant changes in the fuel control, engine or accessories. Proper interpretation of data, in such a format also requires extensive skill and experience. Automatic curve interpretation by use of a digital computer is also an alternative; however, it is considered that this method would require excessive computer capacity and prodigious software preparation. Additional limitations of the analyzer are the inability to simulate dynamic air data inputs which are determined by altitude and Mach number, limiting schedules controlled by turbine out temperature or compressor pressure and compatability relations for variable geometry engines. Some of these inputs could be simulated by modification, with attendant increase in complexity, however, the complete envelope is not achievable with the engine operating statically at sea level. It is also appropriate

to note that this analyzer does not relate directly to any of the four prevalent failure modes being addressed in this study although a fuel control malfunction could most assuredly contribute to hot section distress. Additionally, during the course of this investigation, it was noted that a frequent maintenance action to correct an unknown engine discrepancy consisted of a change of the fuel control which subsequently tested satisfactorily. A device which could thoroughly and reliably test a fuel control while installed on an engine, either at the organizational or intermediate level, would be a valuable tool in a non-integrated engine diagnostic system. The method employed in the Model GS7800 precludes successful development of a practical tester, within the desired time frame, which could be accurately interpreted without excessive personnel training and skill level. Further, in an effort to minimize proliferation of flight line test equipment, it is proposed that, whenever possible, only data recording be performed at organizational level and data analysis and interpretation be performed at a centrally located intermediate level facility.

c. In view of the foregoing limitations and associated economic impact envisioned during a development program, this Fuel Control Performance Analyzer has been judged impractical as an element in the non-integrated engine diagnostic system.

5. Sonic Analysis

a. This technique was initiated in the 1960's and actively continued until the early 1970's in competitive programs conducted by Curtis-Wright and General Electric. The method employed an analysis of the sonic signature generated by a rotating gas turbine, helicopter transmission or accessory gear by using a microphone as a sensor to reveal malfunctions prior to catastrophic failure. Signature analysis is analogous to current vibration analysis except that the sensing device was a microphone responsive to sound waves rather than an accelerometer responsive to mechanical vibrations. Analysis of sonic signature involved a detection of changes in amplitude, harmonic content and modulation character at the discrete frequencies associated with rotating components within the engine.

b. The sonic analyzer has the capability of detecting a limited number of engine malfunctions. The major limitations result from the mechanics of signal transmission. A microphone provides a convenient sensor device; however, to acquire significant data, the sensor must be located as close as possible to the component under examination such as a bearing or meshing gears. This requirement for close proximity is of prime importance to minimize attenuation and avoid interference from extraneous sources. This has been thoroughly substantiated by experimental evidence. In general the microphone is

unable to satisfy this requirement because of size and essentially omnidirectional characteristics. The microphone is also limited in frequency response. Therefore, except under ideal conditions, the desired signal is frequently indistinguishable. In order to obtain a meaningful signal, the fault must generate a pressure wave which exhibits a strong coupling with air, the transmitting medium. While a missing compressor or turbine blade should be detectable, a rotor unbalance and most bearing and gear defects would not generally be resolvable. Evaluation of signal transmission characteristics and coupling coefficients with air indicates which faults might be detected and identifies others as impossible. Some success has been achieved in correlating sonic signatures with discrepant components; however, the majority of test results are characterized as inconsistent and unreliable. Many of the techniques currently employed in vibration analysis originated with analyses of sonic signatures. Although vibration sensors and analyses will be discussed separately, it should be mentioned here that except for the ease of microphone installation, the accelerometer far exceeds the capability of an acoustic sensor in detecting gas turbine discrepancies. In view of known limitations, and negligible current application or ongoing development effort, sonic analysis has not been retained as a potential candidate element for the non-integrated diagnostic system.

6. Optical Pyrometer.

In the field of gas turbine engine diagnostics, this sensor has evolved as a method to monitor maximum temperature in the hostile enviroment of interior engine areas. Increased allowable gas temperatures have accompanied advances in engine design. This permits an increase in energy released within a given volume, increased thrust per pound of airflow and thereby improved overall engine thrust to weight ratio. While higher allowable temperatures have been achieved by metallurgical advances, more significant is cooling of the stress critical rotating turbine blades. Cooling is provided by directing bleed air through the blade interior and exiting through small holes, precisely drilled and located, in the leading edge of each blade. While operating the engine at high power, integrity of this cooling system, including free passage of air through the drilled holes, is essential for blade survival. Data relating cooling air interruption, such as leakage, blocked holes and lapsed time until subsequent failure have not been obtainable. However, it can be expected that blade failure will occur rapidly after any significant air cooling deficiency if the engine is operated at high power. It is in this area that the optical pyrometer is a most useful and important engine diagnostic element. This device is capable, by sensing infrared radiation, of measuring individual turbine blade temperature while the engine is operating. Basically, the system consists of a sensing device optically focused on the target

surface, an amplifier and an output display device such as a meter or cathode ray tube. A typical sensor is a photodiode responsive to .6 - 1.0 microns. The system could be utilized to display either absolute or relative temperature resulting in the detection of either a limit exceedance or an excessive variation between successive blades. Feasibility of this device has been demonstrated in the laboratory and during ground and flight tests. Some problems have been encountered, such as soot formation and time degradation coupled with increasingly higher engine gas temperatures. However, for the purpose of this analysis, it will be assumed that all technical problems have or will be resolved since even then the system is not considered applicable to a non-integrated system. In view of the remote probability of a turbine blade cooling air failure coinciding with a scheduled inspection period established for a non-integrated system and, the likelihood of rapid blade failure in the event of cooling air interruption, it is considered that the optical pyrometer could be justified only if used as a continuous monitor in an integrated system. As the optical pyrometer is currently the only known method to detect this excessive temperature malfunction, the available alternatives, especially in engines with cooled turbine blades, appear to be either integrated or a design of sufficient reliability and/or increased cooling capacity to preclude catastrophic failure.

7. Thrust Computing System.

a. A system has been designed by Computing Devices Company, Ottawa, Canada, to measure and display gross thrust during all flight conditions. Also determined within the system is a reference thrust, defined as that gross thrust which should be produced at military power, for any given flight condition. The cockpit indicator provides a continuous display of actual gross thrust as a digital readout, and on the circumference, a pointer reading percent of reference gross thrust at the existing flight condition. In the engine diagnostic element, the indicated thrust would be compared with reference gross thrust at military power, a deficiency of which would indicate a malfunction in the engine system. The data used for thrust measurement are total pressure at the turbine exit, static pressures at the tail pipe and nozzle entry and, flight dynamics information obtained from the aircraft central air data computer. These data, and certain empirical functions obtained by calibrating a specific engine, are entered into an onboard digital computer to evaluate the thrust equation. The empirical values which are required to determine both actual and reference thrust are unique to each engine and airframe combination. In addition to the required empirical relations, other simplifying assumptions include isentropic flow across the nozzle, fully expanded flow and the perfect gas relation at the nozzle. This system has been installed, for test purposes, on one J-85 engine in a CF-5D aircraft.

Available test results are limited; however, a correlation between measured and predicted gross thrust was indicated. It is conceivable that this system could be utilized as one parameter in arriving at a go/no-go decision immediately prior to take-off or to monitor in-flight engine performance. However, as a diagnostic element, even assuming that results of the required precision could be achieved, it has the serious deficiency of being unable to localize any malfunction. An effective diagnostic system requires measurement of other parameters in the gas path, including those from which thrust could be inferred, which can be obtained more economically and with less complexity.

b. While it is recognized that this thrust measurement system, except for the pressure sensors, could be external to the aircraft, it is considered particularly not applicable to a non-integrated diagnostic system. The non-integrated system has the advantage of being able to select the engine operating point for diagnostic evaluation and thereby assure that variable inlets, nozzles or other devices which could mask actual engine performance are in a known or extreme position. As is discussed in gas path analysis, specific basic parameters are proposed to identify and localize engine malfunctions, particularly those which are of primary interest in this analysis. A system to compute gross thrust predicated on pressure measurements in the gas path is of questionable diagnostic value and superfluous to the gas path analysis method for fault isolation.

8. Holography - Laser Vibration Sensor.

a. These two techniques are of relatively recent discovery with advancement in the start-of-the-art and additions of new and innovative applications occurring rapidly. Principles of holography have been understood since 1947, however, applications were limited prior to laser introduction because coherent light waves are so essential to holography. A hologram is the record of the interference pattern formed between a beam of light carrying information about an object and an undisturbed reference beam. When the recording (usually a photographic plate) is re-illuminated with a light beam similar to the reference beam, the interference pattern diffracts some of the light in this beam in such a way that the object beam is reproduced and continues to propagate almost as if it had not been interrupted by the recording process. An image of the object is formed which is essentially indistinguishable optically from the object itself.

b. The rapid advances being made in the science of holography makes it impossible to establish constraints concerning future applications of this technique to engine diagnostics; however, the most likely current utilization of holography for this purpose would be visualization of stress patterns. In this method, a hologram of the object on which measurements are being made is first produced. The hologram is then illuminated with laser light so that it appears to originate from an object in the same place as the real object. In this way, light reflected from the object can interfere with the light apparently coming from the image. The smallest difference in size or shape between object and image will produce an interference pattern and slight changes in the shape of the object will show up as changes in the interference pattern. This technique will detect changes in size less than a wave length of light. Pictures of stress concentration are obtained by testing components in tension or compression. Welds and flaws in the walls of hollow vessels can be exposed by heating the air inside the vessel and observing the minute variations in the expansion of the walls since weak spots expand slightly more than the surrounding area.

c. There appears to be no current practical application for holography in a non-integrated engine diagnostic system. The major restriction is that the object to be studied must be visible without engine disassembly, therefore, internal engine parts are inaccessible. Additional restrictions are complexity and the requirement that the material to be studied must be loaded, preferably with actual service loads, in order to visualize stress patterns. Combined pressure, thermal and centrifugal stresses are not easily simulated. Holography is not easily adaptable to recording and displaying moving objects. Only simple images have been produced because very costly equipment is required and considerable time is expended. The object must not move more than a fraction of a wavelength of light during the exposure time.

d. A related method of monitoring bearing performance is by use of a fiber optics probe inserted into a bearing housing perpendicular to the bearing outer ring. The output of the probe, when displayed on an oscilloscope, produces a characteristic pattern very similar to a half sine wave. The wave is generated by the passage of balls past the probe and thus, provides an exact measure of ball passing frequency. Variation of the observed passing frequency from the calculated theoretical frequency or fluctuations in the observed frequency are indicative of bearing related discrepancies. Good bearings generate a smooth waveform and the appearance of spikes or discontinuities are associated with ball or race defects. Localization of defects to outer race, inner race

or ball has been reported to be detectable by association with spike or discontinuity spacing. This method, as with monitoring bearings by use of accelerometers, requires direct access to the bearing and is not practical for the non-integrated system. However, it does demonstrate the potential of using light waves for very precise measurements.

e. The laser vibration sensor is predicated on phase modulation of laser radiation which is reflected from a vibrating object. Very accurate displacement measurements, less than the wavelength of light, are achievable by this method. The wavelength of light is less than one thousandth of a millimeter.

f. Two of the limitations pertaining to holography are also present in the laser vibration sensor, complexity and accessibility. Description of a laser vibration sensor system will not be included herein. Ancillary equipment in addition to the laser source for one system arrangement, includes a frequency shifting device, photo detector, amplifier limiter, frequency detector and oscilloscope. In addition, a series of very carefully aligned mirrors and focusing system for the laser signal are required. Skill level requirements for operation, maintenance and data interpretation preclude usage in the operational environment. The requirements for direct accessibility to the vibrating object, similar to accelerometer position requirements due to attenuation effects, would impose the practical limitation of observing only vibrations on the exterior surface of the engine. The piezoelectric accelerometer provides sufficiently accurate measurements for this purpose at each level of maintenance. The precision of a laser vibration sensor could be best utilized during basic research and exploratory development.

9. Thermogram.

This is a device by which relative temperatures are sensed by an infrared detector and displayed on a cathode ray tube. As the detector scans the object of interest, variations in temperature are displayed as shades of black and white, either white hot or black hot and, more recently, as color responses on a color cathode ray tube display. There is no correlation with actual temperature. Possible applications as an engine diagnostic tool would be to scan the engine exterior to detect a local hot spot or to observe temperature distribution in the jet exhaust plume. Localized exterior hot spots could be indicative of inadequate lubrication, internal failure of gas containment structure (combustion liners) or interference between rotating blades and engine casing. Appearance of large temperature contrasts in the exhaust plume could be indicative of clogged or broken fuel nozzles, malfunctioning combustion chamber or failed turbine nozzles. No documentation has been located reporting

this method being utilized or evaluated as a diagnostic device. However, it has been stated informally that attempts to evaluate temperature distributions in the exhaust plume revealed that the unsteady and confused nature of the flow precluded obtaining meaningful results. In order to obtain sufficient data from scanning exterior areas of the engine, removal from the aircraft and test cell operation would be required. The potential of this device for non-integrated purposes is further restricted since many of the faults which could be detected are indicative of advanced deterioration with only limited operating time remaining prior to catastrophic failure. An effective non-integrated system requires that fault detection precede ultimate failure by a sufficient margin of time to preclude occurrence of failure between inspection intervals. It is expected that malfunctions which could be detected by the Thermogram would be evidenced sooner by gas path thermocouples or oil analysis. The Thermogram capability, when considered in conjunction with inherent limitations, is not sufficient to justify inclusion as an element in the non-integrated engine diagnostic system.

10. T-56 Trend Analysis Program.

a. Commander NAVAL AIR RESERVE FORCE INSTRUCTION 13700.1A of 4 June 1975 establishes a standard program to monitor T-56 engine performance and trend analysis applicable to patrol squadrons with P-3 aircraft. The instruction requires recording specific engine parameters as a method of detecting possible engine/instrumentation malfunctions prior to failure. An engine performance trend should be performed at least once every 28 days, when deterioration in engine performance is suspected or when an engine or turbine is changed. When a trend analysis is to be performed, the turbine inlet temperatures are recorded prior to start. Engine start temperatures are then recorded. When the engines have been stabilized at normal RPM, 971°C turbine inlet temperature or 4300 shaft horsepower, recordings are made of shaft horsepower, fuel flow, turbine inlet temperature and % engine performance utilizing the Allison Engine Performance Calculator with inputs of ambient temperature and pressure.

b. This procedure was selected by Naval Air Engineering Center as a prospective candidate to be considered for inclusion in the non-integrated engine diagnostic system. Although experience data has not been received from Commander Naval Air Reserve Force, the measured parameters taken alone are of limited value as a diagnostic tool. The complex interrelationships between engine parameters and judicious selection of performance quantities which best indicate engine health or malfunction has been included in the gas path analysis section. Although the measurable parameters of the T-56 Trend Analysis Program could indicate a malfunctioning engine, the following limitations are applicable:

(1) Inability to isolate fault
(2) Inability to diagnose multiple faults
(3) Delayed diagnosis compared to gas path analysis method
(4) Possible masking of malfunction by variation in significant parameters which are not recorded

c. In the gas path analysis section of this report, it was shown that those parameters best suited to diagnose gas turbine engine malfunctions are fundamental performance parameters such as compressor efficiency and turbine efficiency. Changes in the parameters are used as indicators of engine health and to localize malfunctions. The measurable parameters, such as temperatures, pressures, fuel flow and rotor speeds each make a unique and calculable contribution to the performance parameters. As an example, variations in fuel flow may be more significant than changes in shaft horsepower as an indication of deteriorating turbine efficiency. In the gas path analysis method, relative significance of measured parameters is effected by multiplication of each by influence coefficients. The influence coefficients result from thermodynamic cycle analysis and power balance relationships. A complete example, demonstrating the method and applicability utilizing a J-52 twin spool turbojet has been included.

d. Gas path analysis, as a diagnostic method, has been demonstrated by the U.S. Army with turboshaft engines installed in H-1 helicopters. Implanted faults have been correctly diagnosed. This program is termed AIDAPS (Automatic Inspection Diagnostic and Prognostic System). The first conclusion of this effort as reported in the article, "Gas Turbine Engine Diagnostic Test Results Utilizing a Thermodynamic Analysis Technique", April 1975, by Robert L. Stenberg was, "The last year of test cell work has conclusively shown that thermodynamic analysis can pinpoint major gas turbine engine degradation modes. Flight testing has also indicated that similar defects can be detected by an on-board prototype system." In the same report, it was stated that to maintain gas path parameter measurements within an acceptable band, some instrumentation changes were required. The changes included new compressor inlet pressure and torque sensor transducers and relocation of compressor discharge pressure sensor installation. A similar and additional limitation of the proposed T-56 engine monitor program would result from any non-repeatability characteristics inherent with standard sensors and cockpit instrumentation in P-3 aircraft.

e. Trend analysis or engine performance monitoring in accordance with the method proposed by COMNAVAIRRESFOR is not considered sufficiently effective to warrant inclusion in the non-integrated diagnostic system. However, judicious choice of parameters to identify specific malfunctions, evaluated in accordance with the gas path analysis method and regularly trended, would be a most useful diagnostic device. This method could be evolved relatively easily for the T-56 engine because the thermodynamic parameter interrelationships have been derived and are available. The specific parameters required to be measured would be determined subsequent to evaluation of the influence coefficients that control the relatively simple thermodynamic cycle, with correspondingly few required measurements, and the ability to measure output power of an installed engine.

f. Gas path analysis has been proposed as the primary method to detect the two major failure modes, foreign object damage and hot section distress. These major failure areas were determined by categorizing the causes of 240 engine failures which included torbojet, turbofan, turboprop and turboshaft engines. The T-56 failures only accounted for 18 of the total 240 failures; however, FOD and hot section distress were also the predominant modes at 22% and 17% respectively. Inclusion of gas path analysis, with performance trending, is therefore judged equally applicable to turboprop engines as a prime diagnostic element.

F. EVALUATION OF INCLUDED ELEMENTS. The following paragraphs contain a detailed description and evaluation of each element/system and justification for inclusion of the element/system in a non-integrated diagnostic system.

1. Vibration Analysis. Applied to gas turbine engine diagnostics, vibration measurement is performed to detect mass unbalance including misalignment, bearing or gear irregularities which normally precede rapid failure and the occurrence of damage to the rotating compressor blades due to contact with ingested material commonly referred to as foreign object damage. Each of these malfunctions will be discussed briefly.

a. Mass Unbalance.

(1) Unbalance is the most prevalent cause of vibration in rotating machinery and also the easiest to identify. Two types of unbalance are static or force unbalance and dynamic or moment unbalance. Static unbalance results from unsymmetrical distribution

of rotor mass about the axis of rotation at essentially the same axial location. Rotation of a statically unbalanced body causes a tendency to rotate about the center of gravity rather than geometric center thus generating forces that produce radial displacement at the supporting bearings. Static unbalance may be remedied by placing the rotor on knife edges and adding or removing weight to eliminate the heavy side. Dynamic unbalance is generated by unbalanced forces occurring in more than one axial plane and is detectable only during rotation. Dynamic balance is achieved by separate corrections in each of two planes. During a rotational test, the effects of both static and dynamic unbalance are combined and occur at rotational frequency.

(2) Large acceleration amplitudes at twice rotational frequency are indicative of misalignment. Types of misalignment include offset or angled shaft centerlines, cocked bearings, bent shaft and mechanical looseness. Some types of misalignment are detected at rotational or specific bearing frequencies.

(3) The only vibration measurement recommended for inclusion in the non-integrated diagnostic system at this time is mass unbalance. This would be effected by attaching an accelerometer, externally, to the engine at locations most suitable to measure unbalance of the main rotating components, compressor(s), turbine(s) and accessory gear box.

(4) A piezoelectric accelerometer is the preferred sensor because of superior reliability with no moving parts, smaller size, wider range of frequency and acceleration limits, superior resistance to hostile environment and off the shelf availability to satisfy most requirements. Output of the vibration system is best displayed as average velocity because this parameter is indicative of vibration energy and limitations invariant with frequency, consequently engine rpm, can be established. Velocity is obtained from an accelerometer sensor by electronically performing a single integration.

(5) Whether vibration limits specified in existing 02 (in-test system) and 01 (in airframe) maintenance manuals are meaningful is questionable.

(6) A need exists to document and analyze the vibration signatures of selected Navy gas turbine engines to determine the requirements for meaningful go/no-go vibration checks. Correlation between fixed test system, portable test system and in-airframe limits should be established. Further, a need exists to develop reliable, automated signal analysis technique/equipment to fault isolate in a no-go situation at "O", "I", and "D" levels.

(7) After meaningful vibration data is being obtained at "O", "I", and "D" levels, the data should be input to the Ground Recorder/Analyzer (developed under a gas path analysis program) for centralized engine condition recording and monitoring on an engine serial number basis.

b. Bearing Defects.

(1) Bearings of interest in gas turbine engine diagnostics are made of steel and either ball or roller type. These rolling contact bearings reduce friction by using rolling elements between the bearing shell and shaft in order to replace sliding motion with rolling motion. High bearing vibration levels at unique frequencies result if there are imperfections in a ball, or roller, race or cage (retainer), dirt in the raceway or on the balls, the bearing is cocked on the shaft or in the housing, the shaft or housing is out of round, tapered or egg shaped or if the bearing was improperly installed.

(2) Specific bearing malfunction and associated frequencies are as follows:

(a) Train - created by the train of rolling elements and indicates irregularity of the rolling elements or cage. This frequency is approximately one-third rotational frequency.

(b) Relative Train - Due to relative rotation of the train and the rotating raceway and indicates irregularity of the rolling elements or cage. This frequency is approximately two-thirds rotational frequency and will be accompanied by rotational or other bearing frequencies.

(c) Spin of Rolling Element - Indicative of an irregularity of the rolling element and occurring at approximately twice rotational frequency.

(d) Rolling Element - Due to an irregularity or rough spot on one of the rolling elements as it contacts the inner and outer raceway, alternately, once per revolution. The frequency is twice spin frequency (approximately four times rotational) and has pronounced harmonics due to additional rough spots.

(e) Inner Race - Caused by irregularity, high spot or indentation on the inner raceway, incorrect installation or foreign object lodged on the inner raceway. This frequency is five times rotational with pronounced harmonics due to a number of irregularities.

(f) Outer Race - Caused by an irregularity, high spot or indentation on the outer raceway. This frequency is approximately three times rotational and may have harmonics due to a number of irregularities.

(3) Various methods have been conceived and experimentally tested to measure the mechanical health of installed bearings, identify defects or irregularities and to forecast impending failure. Among these are a fiber optics probe to monitor bearing ring displacement, strain gage attached to bearing ring, electric contact resistance measurement across rolling elements, vibration sensors, variation of capacitance between inner and outer races, ultrasonic-frequency vibration sensors and oil analysis. Except for the latter two, either attachment of a sensor or direct access to the bearing is required. Most effort, in both military and civilian development, has been directed toward utilizing accelerometer sensors to monitor bearing performance and this method has had considerable in-flight utilization. Available technical information is sufficient to conclude that bearing defects and irregularities can be detected by analyzing mechanical vibrations. Success at detecting damaged gears indicative of incipient failure has also been reported.

(4) Although bearing failure is not directly included as one of the four major malfunctions to be diagnosed, its interrelationship with excessive vibration warrants inclusion. It is expected that the major cause of reported excess vibration was caused by mass unbalance or misalignment, although a severely worn or defective bearing could surely be manifested by perceivable vibration. Conversely excessive vibration, from whatever source, will contribute to accelerated bearing failure.

(5) Factors mitigating against inclusion of bearing mounted accelerometers in the non-integrated system included the requirement for extensive and complex instrumentation, inability to retrofit due to practical and economic considerations and relatively low frequency of occurrence of bearing failures. With respect to retrofit, it has been demonstrated that an accelerometer to monitor bearing performance must be located in close proximity to the bearing to preclude the required signal being lost or distorted by attenuation. As an example of the impracticality of installing sensors at each bearing, the J-52 engine has seven main bearings, two of which are dual and one which is internal to the outer shaft. Addition of accelerometers to these bearings would require extensive modification in each of the bearing housing areas and also provisions to leadout the electrical signal from each sensor. Utilization of bearing accelerometers is inconceivable for operational usage unless installation provisions are included during initial engine design.

(6) Probably the strongest justification for not including bearing vibration measurement in the non-integrated system is the development work currently being conducted in the field of oil analysis. This subject is presented in detail in a different section of this report. The ability to predict impending bearing failure by oil analysis particle discrimination appears to be a most promising, simple and reliable diagnostic method which will become available in the near future.

c. Foreign Object Damage. Impact of foreign objects with the rotating blades of a gas turbine is detected by measuring acceleration forces on the appropriate thrust bearing. This method requires that the acceleration is measured at the instant of impact and therefore necessitates an integrated system. The occurrence of a foreign object strike is characterized by a unique, fast rising, high amplitude transient signal. Specific data reporting experimental test results were not found; however, there is general agreement that this is a reliable method to detect the occurrence of a FOD strike. Piezoelectric accelerometers have been utilized for this purpose and because of space limitations are the only acceptable sensor. The signal level to indicate a limit exceedance is determined experimentally and a trip incorporated in the system to indicate occurrence. Multiple limits could be included to better define strike severity. The sensor is continuously monitored but neither recording nor complex analysis is required. The occurrence of an exceedance limit would require further investigation to determine specific location and extent of damage. Multi-rotor installations require a sensor at each thrust bearing. Although foreign object damage is most frequently associated with compressor rotor blades, impact damage to turbine blades would result in a similar vibration signal and therefore preclude absolute isolation to a specific module.

d. Instruments.

(1) Vibration measuring instruments are classified into two fundamentally different types, fixed reference and mass-spring or seismic. In the fixed reference system, one terminal of the instrument is attached to a reference point fixed in space and the other to the object whose motion is to be measured. The method of measuring the relative motion between fixed and moving points could be mechanical, electrical or optical.

(2) In moving vehicles, it is usually not possible to establish a fixed reference point for vibration measurements and therefore seismic instruments are used. The seismic transducer consists of a mass suspended by a spring from the transducer case. Motion of the mass may be damped by a mechanical viscous damper or by electrical current. The transducer case is attached to the moving part and the motion of the mass relative to the case is used to measure vibration. Displacement, velocity or acceleration is measured dependent on the frequency range of interest and whether relative displacement or relative velocity is sensed by the transducer. Transducer response is determined by the undamped natural frequency of the instrument and the amount of damping. As the ratio of forcing frequency to natural frequency is increased substantially above 1.0, the ratio of relative displacement to actual displacement of the moving part approaches 1.0 and the transducer is a displacement measuring instrument. Essentially, the mass within the transducer remains stationary in space and thus the transducer must be sufficiently large to accommodate such a mass with adequate clearance on both sides for the largest displacement amplitude to be measured. The velocity measuring transducer operates in the range well above natural frequency. Velocity between mass and case is measured by a velocity sensing element such as a coil moving in a magnetic field. The velocity measuring transducer is relatively large because of the size of mass requirements and the necessity of containing a magnet.

(3) At the low end of the frequency spectrum or for an instrument with high natural frequency where forcing frequency does not exceed .20 times natural frequency, the ratio of relative displacement of the mass to actual acceleration of the transducer case approaches 1.0. In this range, relative displacement of the mass, which is conveniently measured, is a direct indication of acceleration. The requirement for transducers with high natural frequency is also appreciated since generally only the lower 20% frequency range is sufficiently accurate to be utilized to measure acceleration. If optimum damping is provided, this range can be increased to approximately 60% natural frequency. This disucssion is greatly simplified and neglects spring dynamics and phase relations; however, it is included to substantiate the advantage of measuring acceleration vice velocity to achieve minimum sensor size and the requirement for devices with high natural frequency. The latter requirement is necessary to achieve a flat response curve in which the measured parameter is indicative of acceleration, invariant of forcing frequency, over the frequency range of interest. Instruments with low natural frequency are utilized to measure displacement and velocity whereas those with high natural frequency are used to measure acceleration.

(4) Displacement between the transducer case and the spring-supported mass in a seismic sensor is normally transformed to an electrical signal. This signal may then be transmitted over large distances, further conditioned, recorded and displayed as a function of time for analysis of frequency and waveform of the vibration. A variety of methods are used to effect the mechanical to electrical transformation which utilize variable resistance, capacitance and inductance elements or a combination thereof. A strain gage may also be used as the transducing element. The mass is mounted on a support column which acts as a spring and to which the strain gage is attached. The column natural frequency can be extremely high, therefore, this transducer is normally used to measure acceleration.

(5) A piezoelectric transducer is an accelerometer in which the transducing element is a small disc of piezoelectric material that generates an electric charge when it is compressed or extended. A piezoelectric element in compression may have its fundamental natural frequency as high as 100,000 hz. It is sensitive to small signals and can be made extremely small in size. Low frequency response is limited by capacitive output impedance of the piezoelectric transducer and the input resistance of the circuit to which it is attached. Cathode followers are usually required for measurement of low frequency vibrations. Auxiliary equipment in the form of a charge amplifier is required to process the signals from a piezoelectric transducer.

(6) In addition to the self generating piezoelectric transducer, a passive-circuit type uses piezoresistive material which changes electrical resistance in response to applied force.

(7) In addition to transducer requirements, unless only one frequency band is to be monitored, a spectrum analyzer is required to evaluate the magnitude of vibration at each frequency of interest. The specific quantity measured, displacement, velocity or acceleration is then converted, displayed or recorded for analysis to determine possible limit exceedances and, in conjunction with unique frequencies, to identify the offending component. As a result of the numerous possible combinations of frequency and magnitude, together with associated harmonics accurate interpretation of vibration signals requires considerable skill and experience except in the most simple applications.

2. Borescope. There are several approaches to the early recognition of mechanical distress in aircraft gas turbine engines, and each method can supplement the other. However, one basic technique, and a very powerful diagnostic tool, used in most maintenance systems and all airline approaches is borescope inspection. Many of the symptoms

of deterioration of engine internal components can be assessed through borescope inspection. The presence and magnitude of nicks, tears, rips, rubs, erosions, burns, cracks, buckles, distortions, coating removal and deposits in the compressor, combustion and turbine areas of the engine provide significant and accurate bases for maintenance diagnosis and isolation of damage caused by thermal stress or foreign objects. In addition, borescopes can be used to examine engine accessory drive gear boxes, hydraulic pumps and for discovering foreign objects dropped in engine cavities during maintenance.

a. Equipment.

(1) The basic requirement of a borescope inspection is to provide an acceptable external image of the internal parts of the engine. The quality of the image, which is determined by magnification, resolution, and brightness defines the scope of the manual observation and photographic documentation of the borescope inspection. The engine inspection requirements determine borescope features such as depth of penetration, viewing angle, field of view, illumination intensity, magnification and object distance.

(2) A variety of optical devices are available for borescope inspection. Either a glass optics system housed in a rigid cylindrical barrel or a flexible fiber optics bundle is used to provide an optical image external to the engine.

(3) A current borescope system being applied to a turbofan engine uses a rigid optics train for image transmission, and a glass fiber bundle for illuminating light transmission. The basic system consists of a number of different probes, each having a selected angle of view and magnification, a light source, and the interconnecting glass fiber light bundle. Another system in use today solves the difficult problems of viewing remote and inaccessible areas using fiber optics and a flexible fiberscope.

(4) A fiberscope consists of thousands of precisely aligned glass fibers with an objective lens at one end and a magnifying eyepiece at the other. The objective lens focuses the image, which is then transmitted via internal reflections up the scope to the eyepiece where it is magnified for viewing. A second fiber bundle transmits light down the scope to illuminate the viewing area. This is cold light, so neither heat nor electricity is introduced to the area under inspection. Steerability or deflection of the end tip for maneuvering the scope into inaccessible areas and mirror attachments to permit viewing at angles to the instrument axis are some of the features available with fiberscopes.

(5) Currently available for both borescope systems is the capacity for trend monitoring by application of a Single Lens Reflex (SLR) camera or lightweight, low-light-level TV camera to the borescope output. The borescope-video system provides a real-time image of the internal area of the engine which can be viewed simultaneously by a number of people. By this means, the process of condition monitoring can be eased, operator fatigue minimized, and a conference facility, not otherwise available, provided. In addition, a video tape recording can be made to provide a remote display, facilitate discussion of findings, assist in training operators to use the equipment to best advantage and maintain valuable records for progressive comparison of defects.

b. Requirements.

(1) The effectiveness of borescope inspection of an aircraft engine depends upon the capability of the basic borescope system to extract a useful image from the engine and upon the access provisions for inserting the borescope into the areas to be inspected. In addition, for some applications, a third or operating channel as part of the borescope (fiberscope) would be desirable. This, for example, would allow the spraying of solvents onto the vanes of a gas turbine engine, and the brush capability to wipe these vanes for a more thorough inspection. These criteria are related, since the engine access points set the maximum diameter of the borescope, thus establishing its resolution, illumination, light gathering power, and viewing distance. The maximum diameter of the borescope is one that can be reasonably accommodated between stator vanes at the high-pressure stages of the compressor, through the cooling holes of the outer combustion liner, and between the airfoils of the first stage high-pressure turbine nozzle diaphragm. This normally requires borescope diameters of 0.4 inch or less.

(2) Ideally, to meet the access requirements for borescope inspection, four sets of ports should be incorporated into the turbofan engine. Provisions are required in the compressor case for access between the stator vanes of each stage to allow the inspection of the trailing edges of the upstream rotor blades and the leading edges of the downstream rotor blades as the core engine is turned slowly. In the combustion area, six access ports should be spaced approximately equally around the circumference of the engine. These ports provide access for inspection of fuel nozzles, combustor swirl cups, all areas (forward, middle, aft) of the inner and outer combustor liner, and the leading edges of the first-stage, high pressure turbine nozzle. The stages of the high-pressure turbine blades are inspected through access ports in the turbine nozzle diaphragms and the low pressure turbine blades are inspected through access ports in the respective nozzle diaphrams of each stage.

c. Application/Effectiveness, Present Engine Inventory. Based on NAEC contact with the fleet, borescope use is considered to be satisfactory except in the following areas:

(1) The Lenox Universal Fiber Optic Borescope, Model AE36D-2, while potentially offering some of the necessary traits needed to effectively borescope present engines has proven unsatisfactory. Multiple concentration of black spots at the viewing eyepiece due to broken fibers, poor resolution and insufficient field of view make it impossible to use the image of this scope as a basis for accepting or rejecting an engine. The eyepiece opening is small which makes viewing difficult and fatiguing. Also, the length and flexibility of the Lenox borescope makes it difficult to control the scope and tip position making it inadequate for some applications such as midcompressor inspection. Because of these deficiencies, the Lenox borescope is receiving little use at organizational and intermediate level.

(2) In some cases lack of training in proper borescope operation and interpretation of what is seen has resulted in inability to use existing borescope equipment effectively.

(3) Complete accessibility for borescope inspection was not designed into Navy engines and because of cost and other obvious factors, engine changes now are impractical. However, access is possible through ignitor plugs, fuel nozzles and air bleed ports and limited inspection of compressor, combustion, and turbine areas is feasible to complement other non-integrated engine diagnostic methods. Table IV summarizes access points and the related inspections that can be accomplished on a J-52 engine installed in an A-4 airplane using the correct borescope equipment. As can be seen from this table, accessibility to critical engine areas is possible, and with proper borescope equipment, decisions may be made on engine serviceability without engine removal and teardown. Engines other than the J-52 were not examined; however, similar results would be expected with other gas turbine engines.

TABLE IV

BORESCOPE APPLICATION

Installed J-52 Engine, A-4 Aircraft

ACCESS POINT	VIEWING AREA	REMARKS
Through Compressor	1. Front compressor blades and stators of first two stages. 2. One blade and one stator each of stages 3, 4, and 5 (N-1). 3. Rear compressor 6th stage, by rotating rear compressor (N-2).	Rigid or Flexible Borescope
Low Compressor Discharge Pressure, P_{S3}	1. Trailing edge of 5th stage compressor blades by rotating N-1. 2. Leading edge of 6th stage compressor blades by rotating N-2.	Rigid or Flexible Borescope
Hi Compressor Discharge Pressure, P_{S4}	1. 12th stage exit vanes at seven o'clock position. 2. All 12th stage trailing edge compressor blades by rotating N-2.	Rigid or Flexible Borescope
Fuel Nozzles	1. Six of nine combustion chambers. 2. 1st stage turbine nozzle vanes for the combustion chambers of (1). 3. All 1st stage turbine blades.	Flexible Borescope Not applicable to Model J-52, P-8B.
Ignition Plug	1. #4 and #7 combustion chambers. 2. 1st stage nozzle vanes behind #4 and #7 combustion chamber. 3. All 1st stage turbine blades by rotating N-2.	Flexible Borescope

3. Gas Path Analysis.

a. Gas path analysis in conjunction with appropriate trending has considerable merit as a diagnostic method to detect and isolate the two predominant malfunctions, FOD and thermal distress. This method also has the advantage of being equally applicable to integrated or non-integrated systems although complexity is significantly increased with integration. This method can be adapted to each of the three levels of maintenance and provide useful information at the organizational level without engine removal. It has been effectively applied to stationary and aircraft gas turbine engines.

b. Many methods of gas path analysis have been advocated with a wide assortment of parameter measurement, combination, recording, and display. A method conceived by Mr. Louis A. Urban, Hamilton-Standard presented in his book, "Gas Turbine Engine Parameter Interrelationship," has been investigated for applicability as part of a non-integrated system to detect foreign object damage and thermal distress. The method involves relating independent and dependent parameters through the fundamental physical equations which describe gas turbine engine operation. The dependent parameters are generally the measurable physical quantities such as pressure and temperature at various stations, engine RPM, fuel flow and thrust. The independent parameters consist of performance quantities such as compressor and turbine efficiency, pumping capacity, turbine inlet temperature, compressor bleed air and turbine nozzle area, items which are normally not measurable directly but best describe performance of individual engine components. The basic requirement to initiate this system, and the most complex, is to establish the thermomechanical interrelationship between independent and dependent parameters. This is accomplished by determining the fundamental equations which describe the specific type engine cycle being considered and then, by appropriate manipulation, define mathematically the relation between each applicable dependent and independent variable. The equations are expressed in different form and normalized by a baseline value in order that relative change of the variables rather than absolute value is represented. Typical of the fundamental equations governing the engine cycle are conservation of energy, momentum, continuity, specific heat variation and power balance. Further background details are best described in an article by Mr. Urban which appeared in Journal of Aircraft 1st ed., Vol. 10 No. 7, July 1973 titled, "Gas Path Analysis Applied To Turbine Engine Condition Monitoring".

c. The interrelationship of the parameters is expressed in a matrix format such that each dependent parameter is expressed as a sum of the independent parameters, each multiplied by an appropriate influence coefficient.

Example: Interrelationship between turbine discharge total temperature T_{t_5} and compressor inlet airflow (Wa) for a single rotor turbojet:

$$\frac{\Delta T_{t_5}}{T_{t_5}} = -\frac{k-1}{k}\,\frac{\alpha}{\phi_t}\,\frac{\Delta Wa}{Wa}$$

where:

ΔT_{t_5} = change in turbine discharge total temperature

T_{t_5} = baseline turbine discharge total temperature

ΔWa = change in compressor inlet airflow

Δ = difference between baseline and measured value at a selected engine operating point

k = ratio of specific heats

$$\alpha = \frac{\frac{k-1}{k}\left(\frac{P_{T_3}}{P_{T_2}}\right)^{\frac{k-1}{k}}}{\left(\frac{P_{T_3}}{P_{T_2}}\right)^{\frac{k-1}{k}} - 1}$$

$$\phi_t = \frac{\frac{k-1}{k}}{\left(\frac{P_{T_4}}{P_{T_5}}\right)^{\frac{k-1}{k}} - 1}$$

P_{T_2} = compressor inlet total pressure

P_{T_3} = compressor discharge total pressure

P_{T_4} = turbine inlet total pressure

P_{T_5} = turbine discharge total pressure

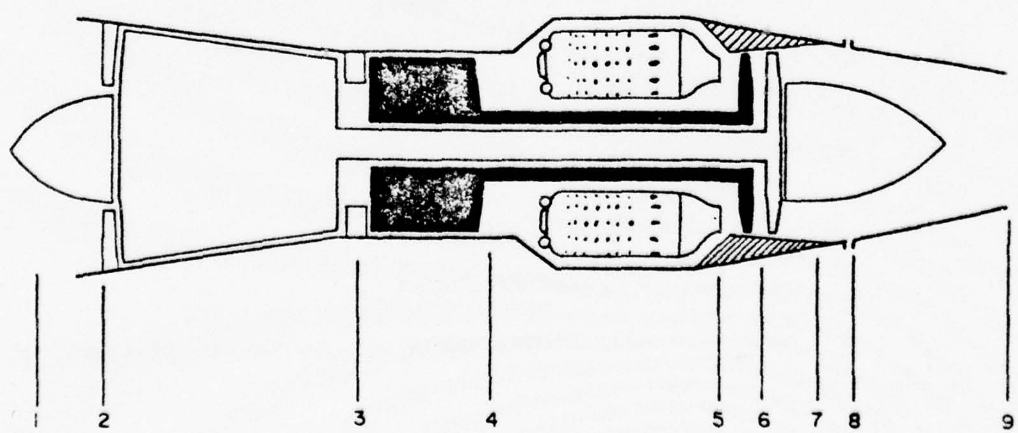
d. The influence coefficient, $-\frac{k-1}{k}\,\frac{\alpha}{\phi_t}$, is computed for the particular pressure ratios of interest and at intervals determined by the expected operating range and required precision of results. Each dependent and independent parameter is interrelated by a similar influence coefficient which is determined by thermodynamic cycle analysis and subsequently numerically evaluated.

e. A chart of parameter interrelationships for a single rotor turbine engine, either turbojet or power turbine is included in Mr. Urban's book, "Gas Turbine Engine Parameter Interrelationship", 2nd ed., Windsors Locks, CT, 1969.

f. In order to demonstrate the Gas Path Analysis method and relate its possible application to a specific current engine, influence coefficients were computed for the J-52 - P-8 engine and applied to test cell data which were extracted from engine logbooks. These data were obtained from fifteen test cell runs on three separate serial engines, performed by both intermediate and depot level activities at five different geographical locations. Each of the test cell runs represented a final acceptance run subsequent to rework, major component replacement or in accordance with normal intermediate level maintenance procedures.

g. Numerical evaluation of the influence coefficients required selecting an engine operating point and assuming representative values when engine characteristic data were not obtainable.

h. The following station numbers are applicable to the twin rotor J-52 turbojet engine.



DUAL ROTOR TURBOJET ENGINE

FIGURE 1

i. The engine operating point selected was engine pressure ratio, $P_{T_7}/P_{T_2} = 2.5$. Variation of thrust, turbine discharge temperature, fuel flow, high compressor rotor RPM, and burner pressure as a function of P_{T_7}/P_{T_2} was determined from data obtained during a J-52 test cell run. After correction to standard day conditions, each of the parameters except burner pressure was noted to vary linearly with P_{T_7}/P_{T_2} over the entire power range from idle to military. Burner pressure variation was linear above $P_{T_7}/P_{T_2} = 2.0$. The equations of each of these lines was determined and subsequently used to translate the actual test cell run data to $P_{T_7}/P_{T_2} = 2.5$.

j. Required assumptions to evaluate the influence coefficients were:

1. $$\frac{P_{T_4}}{P_{T_2}} = \frac{P_B}{P_{T_2}} + 0.5$$

2. $\Delta P_B = .04\ P_{T_3}$

3. $$\frac{T_{T_4}}{\theta_{T_2}} = 2000^{\circ}R\ ;\ \theta = \frac{T}{519^{\circ}R}$$

4. $\Delta T_B = 847^{\circ}$

5. k = 1.40 Cold Section

   k = 1.33 Hot Section

6. Nozzle operating choked

7. $\eta_c = .85$; normal value of compressor efficiency at $P_{T_7}/P_{T_2} = 2.5$.

k. The parameter interrelationship matrix computed for the twin spool J-52 - P-8 engine, using equations applicable to a single rotor engine, is presented in Figure 2. Since the test data to be used were in each case obtained during an acceptance run, it can be reliably expected that the correct match between rotor speeds prevailed. The matrix values should therefore be sufficiently accurate for the intended purpose, particularly when applied to trending performance. This matrix is a set of simultaneous differential equations which mathematically define the change that will occur in each dependent variable as a result of changes in the independent variables.

Example:

$$\frac{\Delta A_N}{A_N} = -1.213 \frac{\Delta T_{T_5}}{T_{T_5}} + 2.088 \frac{\Delta N}{N} - .746 \frac{\Delta W_{a_B}}{W_{a_B}} - 1.680 \frac{\Delta \eta_c}{\eta_c}$$

$$+ .066 \frac{\Delta A_5}{A_5} - 1.918 \frac{\Delta \eta_t}{\eta_t} + .934 \frac{\Delta W_{a_i}}{W_{a_i}}$$

l. A 1% increase in compressor efficiency, and no other change, will decrease compressor discharge total temperature .605%.

m. Since the J-52 engine measurable parameters vary linearly with engine pressure ratio (EPR), it is convenient to select this parameter as the baseline from which changes will be measured. This selection also establishes that $\Delta P_{T_7}/P_{T_7} = 0$. Using this later relation, $\Delta T_{T_5}/T_{T_5}$ is evaluated in terms of the other independent parameters, substituted throughout the matrix, and thereby eliminated. After rearrangement, the equations represented by the matrix of Figure 3 are obtained.

n. Since P_{T_7}/P_{T_2} was chosen as constant, the resulting equations for F_n and A_N are identical and therefore the last equation of Figure 3 is applicable to either parameter.

o. In order to obtain the equations which define each independent variable in terms of the dependent variables, the matrix of Figure 3 will be solved simultaneously for

$$\frac{\Delta W_{a_B}}{W_{a_B}}, \frac{\Delta \eta_c}{\eta_c}, \frac{\Delta A_5}{A_5}, \frac{\Delta \eta_t}{\eta_t}, \text{ and } \frac{\Delta W_{a_i}}{W_{a_i}}.$$

This solution is effected by matrix inversion. After inversion, the appropriate coefficients for $^{\Delta N}/N$ are determined and the desired diagnostic equations are obtained. These diagnostic equations which define the performance parameters in terms of each of the measurable parameters are presented in matrix format in Figure 4.

p. The magnitude of each numerical coefficient in this matrix is indicative of the significance of the measured parameter. For a change in compressor bleed air W_{a_B}: fuel flow, turbine discharge total temperature and thrust predominate and are of relatively equal significance. The matrix also shows that compressor discharge total temperature is the controlling parameter to evaluate compressor efficiency and is also a major contributor to turbine efficiency. There is no provision for measuring this temperature in the J-52 engine. With respect to the relative significance of thrust changes, it is never the dominant factor and appears to be adequately compensated for by other parameters in each equation. Omission or neglect of any measurable parameter infers a zero change.

	$\frac{\Delta T_{T_5}}{T_{T_5}}$	$\frac{\Delta N}{N}$	$\frac{\Delta W_{a_B}}{W_{a_B}}$	$\frac{\Delta \eta_c}{\eta_c}$	$\frac{\Delta A_5}{A_5}$	$\frac{\Delta \eta_t}{\eta_t}$	$\frac{\Delta W_{a_i}}{W_{a_i}}$
$\frac{\Delta T_{T_4}}{T_{T_4}}$	.17	.752	.33	-.605	-.33	0	.33
$\frac{\Delta P_{T_4}}{P_{T_4}}$	.50	2.236	1.0	0	-1.0	0	1.0
$\frac{\Delta W_f}{W_f}$	2.163	1.347	.603	.715	.397	0	.603
$\frac{\Delta T_{T_7}}{T_{T_7}}$	1.344	-.591	.211	.476	.264	0	-.264
$\frac{\Delta P_{T_7}}{P_{T_7}}$	1.885	-.148	1.852	1.918	.066	1.918	-.066
$\frac{\Delta A_N}{A_N}$	-1.213	2.088	-.746	-1.680	.066	-1.918	.934
$\frac{\Delta F_n}{F_n}$	1.588	1.869	2.006	1.170	.164	.932	.836

PARAMETER INTERRELATIONSHIPS - GENERAL

FIGURE 2

	$\frac{\Delta W_{a_B}}{W_{a_B}}$	$\frac{\Delta \eta_c}{\eta_c}$	$\frac{\Delta A_5}{A_5}$	$\frac{\Delta \eta_t}{\eta_t}$	$\frac{\Delta W_{a_i}}{W_{a_i}}$
$\frac{\Delta T_{T_4}}{T_{T_4}} - .765 \frac{\Delta N}{N}$	.163	-.778	-.336	-.173	.33
$\frac{\Delta P_{T_4}}{P_{T_4}} - 2.275 \frac{\Delta N}{N}$	.509	-.509	-1.018	-.509	1.0
$\frac{\Delta W_f}{W_f} - 1.516 \frac{\Delta N}{N}$	-1.521	-1.487	.321	-2.202	.603
$\frac{\Delta T_{T_7}}{T_{T_7}} + .486 \frac{\Delta N}{N}$	-1.068	-.892	.217	-1.368	-.264
$\frac{\Delta F_n}{F_n} - 1.993 \frac{\Delta N}{N}$	.445	-.445	.108	-.683	.934

PARAMETER INTERRELATIONSHIPS $\frac{\Delta P_{T_7}}{P_{T_7}} = 0$

FIGURE 3

	$\frac{\Delta N}{N}$	$\frac{\Delta T_{T_4}}{T_{T_4}}$	$\frac{\Delta P_{T_4}}{P_{T_4}}$	$\frac{\Delta W_f}{W_f}$	$\frac{\Delta T_{T_7}}{T_{T_7}}$	$\frac{\Delta F_n}{F_n}$
$\frac{\Delta W_{a_B}}{W_{a_B}}$	.184	.104	0	-1.346	1.524	1.263
$\frac{\Delta \eta_c}{\eta_c}$	.022	-1.649	.545	.004	0	-.004
$\frac{\Delta A_5}{A_5}$	.118	.257	-1.0	.124	-.271	.822
$\frac{\Delta \eta_t}{\eta_t}$	-.058	1.053	-.514	.830	-1.604	-.811
$\frac{\Delta W_{a_i}}{W_{a_i}}$	-2.267	-.095	0	1.236	-1.867	-.221

DIAGNOSTIC EQUATIONS

FIGURE 4

q. J-52 engine test cell data used to demonstrate applicability of the Gas Path Analysis method is presented in Table V-VII. Engine serial selection was made based on greatest number of test cell data run sheets available in the logbooks reviewed at NAS Oceana.

r. Unique baseline data were applied to each serial engine and were selected as the first chronological test cell run available. Baseline data and subsequent test cell run data were linearly translated to EPR = 2.50 in accordance with the previously determined equations. The Δ value for each measured parameter is the variation from the baseline at EPR = 2.50, normalized by the baseline value. Engine logbooks were reviewed to determine replacement of major components since such changes could effect baseline data. The changes which were recorded are indicated; however, the first cell run data for each serial engine were retained as the baseline. Component replacements, where occurring, were accomplished immediately prior to the recorded test cell run data.

s. Also included in Tables V through VII is the diagnostic performance summary. These values represent the ultimate objective of Gas Path Analysis diagnostics. A sample calculation has been included on each Table. Note that the final performance Δ's have been changed from decimal to percentage values.

t. Ideally, since each test run was a final acceptance run, all performance Δ's would be zero. However, engine variations, average readings and instrumentation tolerances will result in a spread in values even under controlled conditions. Also, in an actual application, a new baseline would have been established upon replacement of major components. In view of the known limitations and the variety of source data utilized in these calculations, the results are remarkably consistent. Allowable degradation limits require experimental determination; however, 5% would appear reasonable.

u. Of more significance than actual numerical values for the purpose of this report, is the consistency between successive tests at the same activity. In almost all cases, these changes are well below 5% indicating good instrumentation repeatability as compared to actual attainable accuracy. It is appropriate to note that variation in performance among engines, each operating satisfactorily, may often exceed the parameter shift resulting from actual faults. It is therefore necessary to track each engine on a serial number basis and, to achieve successful diagnostics beyond a simple limit exceedance method, to trend applicable significant performance parameters. Sophistication of required instrumentation is thus governed by repeatability rather than actual value tolerances.

v. The maximum computed Δ performance change for any of the three engines occurred on engine serial 661167 on 25 November 1972 during tests at NAS Norfolk. Results of this test indicated a compressor bleed air decrease of 11.5% and a turbine efficiency increase of 9.65%. Among the causes of these large indicated performance changes could be instrumentation error, personnel error or compressor rotor change; however, for the purpose of this analysis, the significant data for this run are contained in the measured parameters rather than performances. Measured parameters alone do not portend a large performance change. It is only after converting these data, by application of the diagnostic matrix, to indicate basic performance of specific engine components that the magnitude of change is recognized.

w. An additional advantage of using the influence coefficient method applied to fundamental engine performance parameters is the ability to detect multiple faults. Although dependent measurable parameters such as pressures and temperatures often indicate a malfunction, these quantities alone seldom indicate the fault location and essentially never resolve multiple faults.

x. Gas Path Analysis also includes monitoring and trending individual EGT thermocouple readings and the "spread" between them, where possible. This technique can contribute to hot section fault detection and isolation.

y. Although Gas Path Analysis has other advantages such as adaptability, flexibility and relative simplicity, certain limitations should also be recognized. Most significant among these is inability to forecast impending catastrophic failures or failures resulting from fatigue unless gas path parameters are effected. Extensive cracking within the combustion chambers could also be undetected because frequently this cracking does not effect performance. It is therefore necessary to complement Gas Path Analysis with other diagnostic elements, (e.g., borescopes) to detect incipient mechanical failures not effecting the thermodynamic cycle.

z. The following symbols were utilized in the Gas Path Analysis section:

P_B - Total Burner Pressure

P_T - Total Pressure

T_B - Total Burner Temperature

T_T - Total Temperature

N - RPM

A_N - Nozzle Area

W_{a_i} - Inlet Airflow

W_{a_B} - Compressor Bleed Air

W_f - Fuel Flow

A_5 - Turbine Inlet Nozzle Area

F_n - Thrust

η_c - Compressor Efficiency

η_t - Turbine Efficiency

TABLE V

J52-P-8 ENGINE SERIAL NO. 660981

		OPERATING HOURS				MEASURED PARAMETERS				DIAGNOSTIC PERFORMANCE SUMMARY - %					
DATE	LOCATION	NEW	O/H	EPR	$\Delta N/N$	$\Delta P_{T_4}/P_{T_4}$	$\Delta W_f/W_f$	$\Delta T_{T_7}/T_{T_7}$	$\Delta F_n/F_n$	$\Delta W_{a_B}/W_{a_B}$	$\Delta \eta_c/\eta_c$	$\Delta A_5/A_5$	$\Delta \eta_t/\eta_t$	$\Delta W_{a_i}/W_{a_i}$	NOTE
05/09/72	Jacksonville	1485	---	2.61	BASELINE										
05/09/72	Jacksonville	1485	---	2.40	0	.002	-.024	-.023	.0065	.55	.09	.66	1.06	1.18	
03/06/73	Oceana	1778	293	2.79	-.002	-.009	.010	.035	.0041	4.46	-.49	.38	-4.64	-4.93	1.
10/09/74	Oceana	1864	379	2.75	.001	-.012	.050	.033	-.036	-6.22	-.61	-2.02	2.38	.58	2.
05/08/75	Oceana	2097	612	2.74	-.004	.006	.044	.029	.026	1.70	.32	1.24	-3.39	.35	3.
11/20/75	Oceana	2411	926	2.69	.005	.013	.030	.033	.003	1.46	.73	1.51	-3.74	-3.65	4.

NOTES:

1. Replaced N_1 and N_2 compressors
2. Replaced N_1 and N_2 compressors
3. Replaced both turbines and 1st stages turbine nozzles
4. Replaced rear turbine

EXAMPLE: $\frac{\Delta \eta_c}{\eta_c} = .022(.005) + .545(.013) + .004(.030) + 0(.033) - .004(.003) = .0073$

TABLE VI

J52-P-8 ENGINE SERIAL NO. 677083

		OPERATING HOURS				MEASURED PARAMETERS				DIAGNOSTIC PERFORMANCE SUMMARY - %					
DATE	LOCATION	NEW	O/H	EPR	$\Delta N/N$	$\Delta P_{T_4}/P_{T_4}$	$\Delta W_f/W_f$	$\Delta T_{T_7}/T_{T_7}$	$\Delta F_n/F_n$	$\Delta W_{a_B}/W_{a_B}$	$\Delta\eta_c/\eta_c$	$\Delta A_5/A_5$	$\Delta\eta_t/\eta_t$	$\Delta W_{a_i}/W_{a_i}$	NOTE
10/30/70	Alameda	376		2.73	BASELINE										
10/30/70	Alameda	376		2.50	-.001	.004	-.044	-.038	.006	-.87	.19	.56	1.75	1.75	1.
12/14/71	Lemoore	793		2.84	0	-.007	.051	.003	-.002	-6.66	-.36	1.08	4.27	5.78	
12/14/71	Lemoore	792		2.70	-.006	-.005	.011	.034	.006	-6.01	-.28	1.98	6.17	8.93	
10/25/72	Norfolk	917		2.70	-.001	-.013	.033	.042	-.014	.17	-.69	-.59	-2.18	-3.22	
10/25/72	Norfolk	917		2.56	-.015	-.030	-.038	-.033	-.040	-5.24	-1.66	-.04	7.01	5.74	
01/28/75	Oceana	1241		2.76	-.012	-.006	.018	.022	-.009	-.42	-.34	-.65	-.92	1.03	2.
09/08/75	Oceana	1462	220	2.65	-.001	-.002	.007	.010	-.003	.18	.10	-.24	-.67	-.70	

NOTES:

1. Replaced rear turbine and 1st nozzle guide vanes
2. 01/05/74 - Turned into AIMD Oceana due loud chug and hangup at 75%

EXAMPLE: $\frac{\Delta\eta_t}{\eta_t} = -.058(-.015) -.514(-.030) + .830(-.038) -1.604(-.033) -.811(-.040) = .0701$

TABLE VII

J52-P-8 ENGINE SERIAL NO. 661167

		OPERATING HOURS				MEASURED PARAMETERS				DIAGNOSTIC PERFORMANCE SUMMARY - %					
DATE	LOCATION	NEW	O/H	EPR	$\Delta N/N$	$\Delta P_{T_4}/P_{T_4}$	$\Delta W_f/W_f$	$\Delta T_{T_7}/T_{T_7}$	$\Delta F_n/F_n$	$\Delta W_{a_B}/W_{a_B}$	$\Delta \eta_c/\eta_c$	$\Delta A_5/A_5$	$\Delta \eta_t/\eta_t$	$\Delta W_{a_i}/W_{a_i}$	NOTE
06/12/69	Alameda	485	---	2.70	BASELINE										
06/12/69	Alameda	485		2.46	-.006	-.007	-.049	-.036	0	.99	-.41	.99	2.10	2.02	
08/27/70	Unknown	646	160	2.62	0	-.030	N/A	-.021	N/A	-3.20	1.63	3.56	4.91	3.92	1.
08/16/71	Alameda	762	276	2.71	-.005	-.034	-.017	-.020	-.020	-3.37	-1.86	2.02	5.19	3.20	
11/25/72	Norfolk	1009	523	2.79	.008	-.029	.024	-.013	-.051	-11.50	-1.53	-.54	9.65	4.70	2.
03/26/75	Oceana	1526	1040	2.78	-.001	-.026	.009	.004	.002	-.36	-1.41	2.75	1.28	.55	

NOTES:

1. Replaced 1st stage turbine blades
2. Replaced N_2 compressor

EXAMPLE: $\frac{\Delta A_5}{A_5} = .118(-.005) -1.0(-.034) + .124(-.017) -.271(-.020) + .822(-.020) = .0202$

4. Time and Temperature Recording Indicator (TTRI).

a. Deterioration of gas turbine engine hot section components is influenced by total operating time at elevated or excessive temperatures. Since engines are subjected to different severity of usage as determined by aircraft mission and operator technique, scheduled inspection intervals are established conservatively and based on average usage in order to detect discrepancies prior to catastrophic failure. Hot section inspection is normally the controlling criteria in establishing inspection intervals. Rate of deterioration of metal components operating at elevated temperatures increases with temperature above a predetermined base value. In an effort to measure useful life remaining, the TTRI was designed to sum the total time at which an engine was operated above selected temperature limits. A hot section factor counter is included in the instrument such that counts are recorded faster at higher temperatures. Totalizing time/temperature exposure is progressively recorded and compared with an empirically established standard. The relationship of temperature with deterioration as it effects expending useful life of the metal is not linear but is cumulative and therefore provides a good indicator of impending failure. Useful life is expended at an increasingly faster rate as operating temperature is increased above the predetermined base value. The TTRI also incorporates three overtemperature warning flags to indicate exceedance of specific temperature. This instrument has been utilized to monitor engines installed in F-8, F-102, F-105 and F-106 aircraft and results indicate a significant reduction in engine failures was achieved. The TTRI is now installed in all F-106 aircraft. It has proven itself to be extremely reliable and resultant data are used as a basis for maintenance decisions.

b. The latest version hot section monitor available is the Howell Jet Engine Monitor (JEM), a sophisticated time temperature recorder.

c. An additional benefit results from correlating excessive hot section counts as indicators to engine malfunctions during particular flights. These malfunctions were subsequently attributed to the basic engine, instrumentation, fuel control malfunctions or improperly trimmed engine. The results which have been reported are impressive and the basic theory is considered sound.

d. Low Cycle Fatigue (LCF) is recognized as an important parameter to measure the useful life of many engine components. The requirement for a LCF counter is now included in General Specifications for Engines, Aircraft, Turbojet and Turbofan, MIL-E-5007D. This specification states that the LCF counter shall have provisions for counting separately at least four LCF events and that a relative

damage chart showing the damage assessment for each LCF event in percent of takeoff damage be provided. Damage assessment for both hot and cold section is segregated. In addition to takeoff, other LCF events could include touch-and-go landings, combat subsonic cycles, combat supersonic cycles, ground run ups and in-flight RPM excursions. Low Cycle Fatigue is defined as the cumulative damage which occurs in the cycliclly loaded parts of the engine as the rotational speed of the major rotational parts increases and decreases. Damage mainly results from centrifugal stresses, but the effect is compounded by material temperature. It is analogous to damage in aircraft structural components, particularly the main spar, which accrue from cyclic acceleration forces. They are recorded by the installed counting accelerometer as exceedances of selected "G" levels in tactical aircraft.

e. Instrumentation to record hot section count and low cycle fatigue count requires an integrated system. Development and use of this type equipment should be considered by cognizant NAVAIRSYSCOM propulsion groups. Flight to flight results would be a useful manual input to the Ground Recorder/Analyzer (developed under a gas path analysis program) for permanent recording and monitoring.

5. Navy Oil Analysis Program.

a. Discussion.

(1) Oil, in addition to its lubricating and coolant qualities, in a gas turbine engine, acts as a carrier of information in the form of wear particles produced by the oil wetted engine components. Contained in a small oil sample, is a myriad of wear particles, interpretation of which can provide information of how wear surfaces are faring and the conditions under which these particles were formed. This information, available through some form of oil analysis, is not obtainable through other engine health monitoring methods such as gas path analysis and borescope inspections.

(2) The technical basis of the Navy Oil Analysis Program (NOAP) is the measurement of the amount and type of wear metal in the engine/component oil system, determining whether the volume of these contaminant constituents in the oil is normal or abnormal and subsequently taking the appropriate action using known wear metal baselines for the engine/component being monitored.

(3) The two most commonly used methods of evaluating wear metal in oil are the emission spectrograph and the atomic absorption spectrograph. Of the two, the emission spectrograph is the more widely used today because of its ability to analyze samples in the as received state, analyze more than one element at a time, greater

adaptability to different operating locations, and because it allows automatic transcription of the results to standard forms and punched cards or tape.

(4) Oil analysis has been documented as being responsible for a substantial number of valid engine removals. The removals before failure have resulted in many tangible and some intangible benefits, such as maintenance saving due to prevention of secondary engine damage and more importantly, flying safety. This study relates the effectiveness of the oil analysis program as it now stands and evaluates the potential effectiveness of new techniques currently in development.

(5) During the six month period ended June 1972, 39% (28) of 72 gas turbine engines removed because of Navy Oil Analysis recommendations had negative findings (no discrepancy noted) on disassembly. Also during this period, 143 gas turbine engines were removed because of metal contamination in the oil systems, 14% (20) of these engines were being monitored by the Navy Oil Analysis Program (NOAP) but had not been identified by NOAP as discrepant.

(6) In December 1975, a J-52 engine installed in an A-4 aircraft, was removed based on discovery of wear metal by detection equipment that was being used to augment NOAP. Oil samples taken up to the time of engine removal, and samples taken at the Naval Air Rework Facility, Jacksonville, Florida, after engine removal revealed no abnormalities by Navy analysis. Disassembly revealed the main oil pump, the #6 bearing scavenge pump, and both the #4½ and #5 bearings damaged beyond repair.

(7) Naval Safety Center records for a five year period revealed that 19% of the engine related major accidents resulted from failure of oil wetted components. It could not be determined whether the engines involved were under an oil analysis program.

(8) The above cited situations indicate the need for improvement of the oil analysis program. Deficiencies in the Navy Oil Analysis Program are related to procedural factors and inherent technical limitations.

(9) The success of the Navy Oil Analysis Program is dependent upon certain critical procedural factors. These factors are sampling integrity, sampling interval, transit time, and communications between user and laboratory. Using these factors as guidelines, an evaluation of the Navy Oil Analysis Program (NOAP) was conducted at two Naval Air Stations.

(10) Sampling integrity is of primary importance because introduction of foreign contaminants in the oil sample during the sampling process and/or during subsequent handling through improper sampling techniques or duplicity, will cause erroneous results. Detection of erroneous samples is difficult, however, evidence of some lack of sample integrity was revealed in that there have been instances of clean unused oil being received at the analysis laboratory or oil from each engine of a multi-engine airplane being identical indicating all samples were taken from the same engine.

(11) Sampling intervals for five different model engines were determined from NARFP 13710/957 Forms (Oil Analysis Record) and compared with the intervals specified in NAVMATINST 4731.1, Navy Oil Program. The specified intervals were exceeded in all cases. For example, the specified sampling interval for the J-57 engine is 10 hours, actual sampling interval averaged 31.7 hours. For the J-79 engine, the specified interval is also 10 hours, actual sampling interval averaged 18.1 hours.

(12) The transit time from squadron to laboratory of the oil samples for the engines discussed above were 4.4 and 5.3 days respectively. Examination of records for 5 different model engines revealed an average transit time of oil samples of 4.4 days. Times in excess of 10 days were common during the record examination.

(13) Excessive transit times delay NOAP analysis and increase the probability of engine/component failure before detection. The time from detection of an abnormal condition to failure is unpredictable and may be as soon as the next flight. Good communications between user and the laboratory is essential in oil analysis. The service provided to operating activities culminates in recommended maintenance actions by the laboratory based on sample results. During the examination of oil analysis records, instances of lack of response and feedback to laboratory recommendations were noted, e.g., a recommendation was made for Advice Code N (Change oil, sample after 10 minutes run and after 5 hours operation. Submit samples for analysis). The samples were submitted after 31 flight hours. An Advice Code H was recommended (Inspect filters and sumps before flight, report findings and submit check sample, without oil change, by most expeditious means). The recommendation was given on day 5335 and, as of day 6036, no action had been reported.

(14) Squadron initiated feedback information as delineated in NAVMATINST 4731.1 is generally not being provided. This instruction requires operators to submit an oil sample and a Maintenance Feedback Form (NAVMAT 4731/1) to a laboratory after completion of maintenance that would effect the oil-wetted system, such as an oil pump change. A review of the records revealed only a modicum of any such entries.

(15) Technical limitations in the present Navy Oil Analysis Program also reduce its effectiveness as a diagnostic method. Basically, NOAP determines wear metal particle concentration in PPM (Parts Per Million) and identifies element metals contained in oil.

(16) The particle detection range of NOAP is approximately 1-8 microns; however, it does not differentiate between particle sizes within this range, and it is essentially insensitive to particles larger than 5 microns. This limitation is a serious drawback in the detection of incipient failure.

(17) Table VIII summarizes the six wear regimes identified in tests conducted on steel surfaces in sliding contact. As can be seen from this table, wear rates do not become significant until free metal particles exceed 15 microns, an area where NOAP is blind to particles of that size.

TABLE VIII

WEAR REGIMES

Regime	Particle description and major dimension	Surface description	Wear rate
1	Free metal particles usually less than 5 μm	Varies between polished and very rough. One surface can be polished while the opposing surface remains as generated.	Approaches zero
2	Free metal particles usually less than 15 μm	Stable, smooth, shear mixed layer with a few grooves depending on the number of particles in the oil.	Low
3	Free metal particles usually less than 150 μm	Ploughed with evidence of plastic flow and surface cracking.	High
4	Red oxide particles as clusters or individually up to 150 μm	Ploughed with areas of oxides on the surface.	High
5	Black oxide particles as clusters or individually up to 150 μm	Ploughed with areas of oxides on the surface.	High
6	Free metal particles up to 1 mm	Severely ploughed, gross plastic flow and smearing	Catastrophic

(18) Studies done by NAVAIRENGCEN also support the value of particle size and particle size distribution in detecting failure in oil wetted systems. In a report of bench testing roller and ball bearings until failure, oil specimens were periodically sampled from the lubricant systems and subjected to numerous particulate analysis techniques. The summary concluded that a plot of the large wear particles, 5-20 µm,

substantially reflected surface wear over the life of the bearing whereas Navy analysis exhibited only slight reading variation during the same period and was ineffective in predicting roller and ball bearing failure. At the Oil Analysis Program Semi-Annual Coordination Meeting, 31 March 1976, sponsored by NAVAIRENGCEN, it was reported that of 28 roller and ball bearings run until failure, NOAP predicted failure of only three.

(19) Another NOAP technical limitation is that the spectrometer reports elemental analysis but is blind to chemical form. Therefore, NOAP is unable to differentiate between wear metal particles and the metal's corrosion product. Erroneous laboratory recommendations will result unless the laboratory suspects corrosion and a lengthy analysis undertaken to remove any uncertainty.

(20) The inability to determine particle shape is also a technical limitation of NOAP. Recent work in the area of particle shape determination with the use of a scanning electron microscope has revealed specific details of wear particle shape. Rubbing or adhesive wear metal particles found in the lubricants of machines are in the form of platelets and are indicative of normal or permissive wear. Cutting or abrasive wear particles take the form of miniature spirals, loops and bent wires and a concentration of such particles is indicative of a severe, abrasive wear process. A sudden increase in the number of such particles in successive oil samples indicates imminent failure. Particle morphology offers promise in improving detection and prognosis.

(21) Determining wear particle rate of production is not a NOAP limitation, however, it is a capability of NOAP that is not being exploited. A refinement to the Navy approach to NOAP, particle rate of production is used by airlines through the application of a dilution correction equation to the NOAP reading. This mathematical correction program eliminates the effect of fresh oil dilution which may camouflage incipient failure. The rate of increase criteria enables excessive wear and therefore incipient damage, to be detected at a much earlier stage then could be detected using absolute limits or direct measurement of wear metal concentrations in parts per million. In tests run on a Pratt & Whitney JT9D-3A aircraft engine under controlled test cell conditions, an intentionally damaged bearing was installed to simulate a failure mode. Successive oil samples were analyzed during the test run. There was no difficulty in detecting the abnormality using the rate of wear metal increase. No conclusions could be made using standard NOAP methods based on sample concentration alone.

(22) The Air Force is conducting a program using wear metal rates as a basis for engine health monitoring of the TF-41 engine. Results thus far indicate that wear metal production rates are an improvement over standard methods and that it is possible to predict an engine failure more reliably and at an earlier time using this method.

b. Equipment Developments. Table IX summarizes state-of-the-art methods for detecting wear debris in oil samples.

TABLE IX

OIL ANALYSIS METHODS

METHOD	SIZE RANGE DETECTED (μm)	LIMITATIONS
NOAP	0.65 - 8	Blind to composition, size, and shape
FERROGRAPH	0.1 - 20	Paramagnetic and ferromagnetic particles only. Simplified version, blind to composition, size, and shape.
PARTICLE COUNTER	1 - 9000	Blind to composition and shape
LIGHT SCATTERING	0.1 - 8	Blind to composition, size, shape
MAGNETIC CHIP COLLECTOR	25 - 400+	Magnetic only
FILTRATION CHIP COLLECTOR	250+	Coarse and conductive only
TEST PATCH	.45+	Used as a go/no-go test. Size range depends on filter size.

(1) Ferrograph Method - In Analytical Ferrography, the oil sample, diluted with a special solvent to promote precipitation of wear particles, passes over a glass slide placed over the pole-pieces of a high gradient magnet. This pulls out the iron and iron oxide particles, and displays them with the largest pieces at the entry point, followed

by a regular progression of smaller sizes. The slide is then examined by a special microscope under bichromatic illumination, which shows the metal as red and the oxide as green or yellow. A simplified version for use in maintenance shops is equipped with photodensitometers at two points, representing coarse and fine particles. The digital reading at these two points, is proportional to the percentage of the area covered by opaque particles. These readings, especially their ratio, give a quick picture of the magnetic particles population and some insight as to the wear mode. The ferrograph is blind to nonmagnetic particles, however, it will pick up paramagnetic material and even nonferrous metal with steel specks.

(2) Particle Counters - Liquid containing the particles to be measured is passed by the photodiode (sensor) where an amount of light proportional to the particle size is blocked, the particles' size and number are sensed and sent along a cable to a counter and are displayed. These particles may be categorized in from one to six size ranges as selected by the operator and are measured regardless of their makeup, or color characteristics. The instrument is capable of counting up to 4,000 particles per second and can analyze particles per fluid volume or size distribution alone. Each sensor has a size measurement ratio of 1:30 from smallest to largest particle. Therefore, the operator using the 5-150 micron sensor could select for example, any six size ranges from 5 to 150 microns. This instrument can be used in the laboratory or in the field, in-line, where the operator attaches the system to the equipment to be tested by means of quick disconnects, the numbers recorded, and the quick disconnects removed. It is capable of determining particle size and particle size distribution but does not resolve composition and shape. It also responds to organic matter, emulsified water and air bubbles.

(3) Light-Scattering Meters - Most light-scattering meters use a dual-beam to measure light absorption and scattering. This design avoids loss of sensitivity due to darkening of the oil when the two signals are combined in a compensator. Two solid-state light sources are energized alternately. One source provides a reference beam which produces light signals in the scattering and attenuation photo-sensors. The other light source projects a beam through the oil, which produces scattering and attenuation signals in the same photo-sensors. The scattering photo-sensor, therefore, receives light pulses which alternate between those resulting from light scattered from particles in the oil, and from the fixed scattering reference. The attenuation photo-sensor similarly receives pulses which alternate between those resulting from oil attenuation and the attenuation reference. Limitations are inherent in the sensing method; in addition to being blind to coarse chips, the light-scattering meter responds to organic matter, emulsified water and air bubbles.

(4) Chip Collectors - a chip collector is a device that retains relatively coarse wear debris. The modes of collection have two different forms, magnetic chip collectors and filtration collectors which may incorporate alarms and include provisions for quick visual inspection. Magnetic chip collectors are used by British European Airways (BEA). BEA does not use a reporting collector, but inspects the plugs on a 25 hour or 50 hour basis depending on engine type. The plugs, with debris untouched, are sent to a control unit where the debris is examined by microscope. The chips are taped to a file card and become part of the engine record. Periodic inspection of debris collected in filters is used to complement magnetic plug collectors. Filtration collectors do not include the usual basket filter which reports only when dangerously full. The newer devices use two or more electrical circuits to indicate 10%, 20% or more of the filter is covered with metal. These devices have the advantage of collecting and reporting all kinds of metal, rather than being blind to nonferrous metal. Like the magnetic collectors, the filter units can be pulled out and sent to the laboratory for further examination.

(5) Patch Test Analysis - A technique that potentially shows much promise and deserves further study is Patch Test Analysis. This test is presently being used in the Navy at organizational level for detecting contamination levels in hydraulic fluids. A Patch Test Analysis Kit contains the filter holder assembly, filters and other necessary items to run an elementary test. The test consists of taking a sample of fluid, passing this fluid through a Millipore filter, flushing with freon, and then making two basic tests. The first is an examination of the filter for visible metallic and nonmetallic particles. The second is a color comparison of the filter with standard patches provided with the kit. Standards for hydraulic fluid are presented in Table X. Discussion with fluid experts indicate, notwithstanding the simplicity of this test, that results are good and, with minor changes, could be adaptable to oil analysis. Expected changes required are filter size, sample size and color standards. Two examinations were made using this method with .45 micron filters and the results of both were impressive. The first was a patch analysis on a failed JT15D engine that showed satisfactory NOAP readings even after failure. The patch test showed unsatisfactory oil on both its measures, visible metal and a patch many times darker than the acceptable standard. The second test consisted of running spectrometric liquid calibration standards (0 PPM, 3 PPM, 10 PPM, 50 PPM, 100 PPM) through the filter and comparing changes in color. Patch color changes indicated increasingly significant particle contaminants. The main advantage of the patch test as a supplement to oil analysis if proven acceptable, is its simplicity and the fact that the kits are already in use at the organizational level of maintenance.

TABLE X

NAVY STANDARD FOR AIRCRAFT AND GSE HYDRAULIC FLUIDS

Micron size range	Particle contamination level - by class						
	0	1	2	3	4	5	6
	Total number of particles/100 milliliters sample						
5-10	2,700	4,600	9,700	24,000	32,000	87,000	128,000
10-25	670	1,340	2,680	5,360	10,700	21,400	42,000
25-50	93	210	380	780	1,510	3,130	6,500
50-100	16	28	56	110	225	430	1,000
Larger than 100	1	3	5	11	21	41	92

c. Summary.

(1) The ineffectiveness of NOAP can be related to the number of false engine removals based on NOAP recommendations (misses) and those engine/component oil lubricated failures that were not detected through oil analysis (fails).

(2) Reasons for misses have not been documented. Incomplete disassembly inspections and self-correcting or minor defects, hence undetectable on tear-down, may be contributors.

(3) Communications could be a factor. Failure to report time since oil change, time since new or overhaul, or the changing of an engine component where wear-in is a factor make correct analyses difficult. Mistakenly identifying oil corrosion products as wear metal and conflicting reports from maintenance shops and the evaluators concern over safety, influencing him to err on the conservative side, produce misses.

(4) Whatever the cause, the miss rate is high and deserves investigation.

(5) The failure of NOAP to detect oil lubricated engine/component incipient failure results from the inherent technical limitations (blind spots) of NOAP and to a lesser extent, procedural weaknesses.

(6) A refinement to NOAP is the computing of particle rate of production. Studies show that this technique offers earlier and more positive detection capability than the particle concentration method now being used.

(7) Wear particle detection capability is the basis of the methods listed in Table X. The ferrograph, particle counter, and light-scattering appear to be potential candidates to replace NOAP. However, until one of these fine-particle counters can prove superior capability at the operational level, spectrometric analysis will continue to be the basis for the Naval Oil Analysis Program.

(8) Consideration must also be given to ultrafine filters in the 3 to 5 micron range which are being incorporated into future engines and retrofit into existing engines. Particulate content in the filter will have to be monitored.

(9) NAEC is continuing the Oil Analysis Methodology Development Program to develop an effective oil analysis equipment/ technique by:

(a) Researching presently available oil analysis information.

(b) Modifying oil analysis sampling techniques based on ultrafine filtering effects.

(c) Modifying the oil analysis monitoring technique and monitoring criteria based on results obtained from the NAEC Oil Analysis Research and Development Program.

(d) Verifying the new methodology by field testing.

6. Trim Testers and Jetcal Analyzers. This equipment is used at "O" level for engine trimming, engine troubleshooting and temperature system checks. The Jetcal Analyzer is also used at "I" level for temperature sensing system checks.

a. Engine Trimming and Troubleshooting.

(1) Equipment currently in use to perform these functions are Jetcal Analyzers, trim testers "unique" to particular engine/aircraft combinations, the A/E24M-28 Trim Tester for G.E. engines and the TTU-347/E Trim Tester for PWA engines.

(2) The parameters measured by the trim tester are generally included in cockpit instrumentation, the notable exceptions being variable geometry angles (inlet guide vanes) and low compressor rotor speed in dual rotor engines. The trim tester instruments are more accurate than those installed in the cockpit and therefore more precisely measure critical parameters, allow accurate adjustment of engine controls and verify the satisfactory calibration of cockpit instruments.

(3) Specific limits and relations between the engine parameters, temperature, pressure, RPM and fuel flow, are normally established by the engine manufacturer. The purpose of the trim tester is to allow very accurate adjustment of these parameters, on aircraft, to assure a properly performing engine. Inability to compensate within limits or specific exceedances constitute indications of a malfunction. Exceeded parameter limits and combinations thereof are utilized to isolate malfunctions.

(4) The A/E24M-28 and TTU-347/E Trim Testers were developed to provide the capability of trimming most G.E. and PWA engines. PGSE (Peculiar Ground Support Equipment) adapter kits are required for specific engine/aircraft combinations.

(5) The following is a summary of the parameters that are measured, including units, accuracy requirements and other functions performed by each trim tester. Each trim tester provides digital readouts.

A/E24M-28 TRIM TESTER FOR G.E. ENGINES

PARAMETER	ACCURACY
Gas Generator - % RPM	$\pm 0.2\%$
Fan-RPM/Power Turbine - % RPM	± 20 RPM/$\pm 0.2\%$
Turbine Out Gas Temperature - ^{o}C	$\pm 2^{o}C$
Variable Geometry Angle - Degrees	$\pm 0.2^{o}$
Ambient Temperature - ^{o}C	$\pm 0.5^{o}C$

ADDITIONAL FUNCTIONS

Correct RPM/%RPM and turbine out gas temperature to standard day conditions.

Supply variable DC millivolt signal to aircraft's cockpit temperature indicator while simultaneously displaying equivalent temperature on test set.

TTU-347/E TRIM TESTER FOR PWA ENGINES

PARAMETER	ACCURACY
N_1 Rotor Speed - % RPM	$\pm 0.2\%$
N_2 Rotor Speed - % RPM	$\pm 0.2\%$
Turbine Out Gas Temperature - ^oC	$\pm 2^oC$
Pressure - in. Hg (Total inlet, total exhaust or ambient)	± 0.25 in. Hg

ADDITIONAL FUNCTIONS

Correct %RPM and turbine out gas temperature to standard day conditions.

Divide total exhaust pressure by total inlet pressure and display ratio on test set.

Supply variable DC millivolt signal to aircraft's temperature indicator while simultaneously displaying equivalent temperature on test set.

(6) The BH111 and BH112-J46 Jetcal Analyzers include an EGT and %RPM capability and therefore can be used on some engines where these trim parameters are required.

(7) The Jetcal Analyzer and "unique" trim testers have low reliability and high maintenance and operating costs and are being replaced by the G.E. and PWA trim testers where considered economically feasible.

(8) There appears to be no need in the near future for the development of additional trim testers except for the following: A new design TF41 TLA (Temperature Limiter Amplifier) Test Set is being developed because of the long history of persistent problems regarding reliability of the test set and associated connecting cable sets. The A/E24M-28 and TTU-347E Trim Testers cannot be adapted to this engine because of "very unique" trim parameter requirements.

(9) The measured parameters required for trim testing are among those which would be included in gas path analysis; however, absolute accuracy standards are more restrictive for trim testing when compared to gas path analysis. Assuming gas path analysis is pursued, automatic data recording and processing is envisioned as part of the latter phase of development. This same system would be

directly adaptable to recording and displaying trim parameters. The accuracy requirements of measured parameters utilized in gas path analysis are far less severe because results are trended where repeatability of successive measurements rather than absolute accuracy is the controlling criteria. The combination of gas path analysis and trim testing is analagous to an integrated system except that parameters are recorded at selected intervals during ground operation and data analysis is performed at a ground terminal rather than monitored continuously while airborne.

b. Temperature Sensing System Checking.

(1) The Navy philosophy on checking and calibrating the turbine exhaust gas temperature indicating system at "O" level is to use trim testers to perform "dynamic" (engine running) system checks and Jetcals to perform "static" (engine not running) checks.

(2) The "static" check with a Jetcal Analyzer is performed with the engine either installed in the aircraft or on a test stand. The latter test is limited to thermocouple performance as airframe components are excluded. In airframe, the check is accomplished by placing a heating element over each engine thermocouple probe, adjusting the heating element to a controlled temperature and noting the average temperature readings displayed simultaneously in the cockpit and on the Jetcal Analyzer. This is only possible where the engine thermocouple probes are accessible to the mechanic.

(3) The "dynamic" check is performed on engines which permit individual EGT thermocouple readings. It is not performed on engines which have integral harnesses in which all EGT thermocouples are paralleled together. It can be performed with the TTU-347E Trim Tester, but the Jetcal Analyzer and "unique" trim testers require additional equipment. Temperature readings on the test set indicator and the cockpit indicator of the average and individual thermocouple readings are analyzed to make the verification. This technique can also contribute to hot section fault detection and isolation.

(4) There are certain conditions where engine operation is not possible (e.g., where the aircraft is on the hangar deck of a carrier) and a static check is the only test possible. If the thermocouple probes are not easily accessible, the use of the Jetcal Analyzer is still not a viable solution. A new method of static check is needed.

(5) An Aircraft Engine Temperature System Tester study was conducted by NAVAIRENGCEN in FY-75 and an interim report, NAEC-GSED-MISC-157 was published. Preliminary work on a new method for statically checking EGT systems was completed; however, the effort was not funded

in FY-76 or FY-77. Several engine manufacturers are pursuing the new approach independently. Development of such a system would permit elimination of the Jetcal Analyzers.

G. ECONOMICS OF ENGINE DIAGNOSTIC SYSTEMS. One of the more significant factors to be considered in prejudgment of an engine diagnostic system is the economics of its installation and application.

1. The value of tangible benefits realized takes the form of savings in terms of:

a. Quick reaction to engine malfunctions resulting in a more effective combat readiness posture.

b. Reduction of catastrophic failures and resultant loss of lives and aircraft.

c. Reduction of required spare parts.

d. Elimination of unnecessary overhauls and reduction of in-depth overhauls.

e. Improved quality of maintenance.

2. The Naval Safety Center documented 53 aircraft accidents directly attributed to engine failure during the five year period ending August 1975. This equates to slightly less than one accident per month. During the present fiscal year (July 1975 - March 1976), there have been 102 major aircraft accidents or an average of about 10 accidents per month. The average cost per major accident is conservatively estimated at $2,000,000. Approximately 17% of major aircraft accidents are engine related.

3. Basic engine costs and their respective overhaul costs, computed at 10% of engine cost, are depicted in Table XI, Engine Data Matrix. Assuming that the installation and application of a diagnostic system will effect a 1% - 10% savings in overhaul costs, primarily through early fault detection and elimination of secondary damage, a straight line reduction of these costs is realized. Whenever a functional part is introduced into the repair/overhaul cycle, through fault diagnosis, significant savings result.

4. A recent study of costs of engine monitoring in commercial operations yielded an average cost of $0.90 to $1.45 per engine operating hour. A breakdown of cost reveals that 10% is for oil monitoring, 20% for performance monitoring,

10% for data collection, 20% for data processing and 40% for engineering evaluation of the data. Further research into the economics associated with a commercial engine diagnostics revealed that from February 1973 to February 1974, JT-8D engines in 27 dual engine aircraft were monitored. They amassed a total of 253,000 operating hours and 30 premature removals were documented, 60% of these, or 18 engines, were detected by performance monitoring. The cost of prematurely removing these 18 engines was $505,000; however, if the 18 engines had been allowed to operate until failure, the cost would have been $1,410,000. This represents a reduction in operating costs of $905,000.

5. Table XI further depicts the significance of the Navy's inventory investment in the selected engines. Non-integrated diagnostic systems would support and complement this investment. Decreased maintenance and increased time between overhauls results in additional engine availability. This would conceivably allow a reduction of total inventory and subsequently increase the Operating/Value Ratio (number/$ installed engines to number/$ inventory engines). Figure 5 graphically displays these ratios. This economically advantageous concept would be much more pronounced when considering single engine aircraft engines and the reduction of in-flight failure situations where resultant costs reflect total aircraft vice engine costs.

6. The cost of a diagnostic system in terms of the recommended elements/techniques constitutes a small order of value in a phased implementation plan when considering inventory value and the resultant reduction of recurring costs of spare parts, overhaul, maintenance and loss. Detailed cost analyses must be generated for each diagnostic system equipment/technique during exploratory and full-scale development.

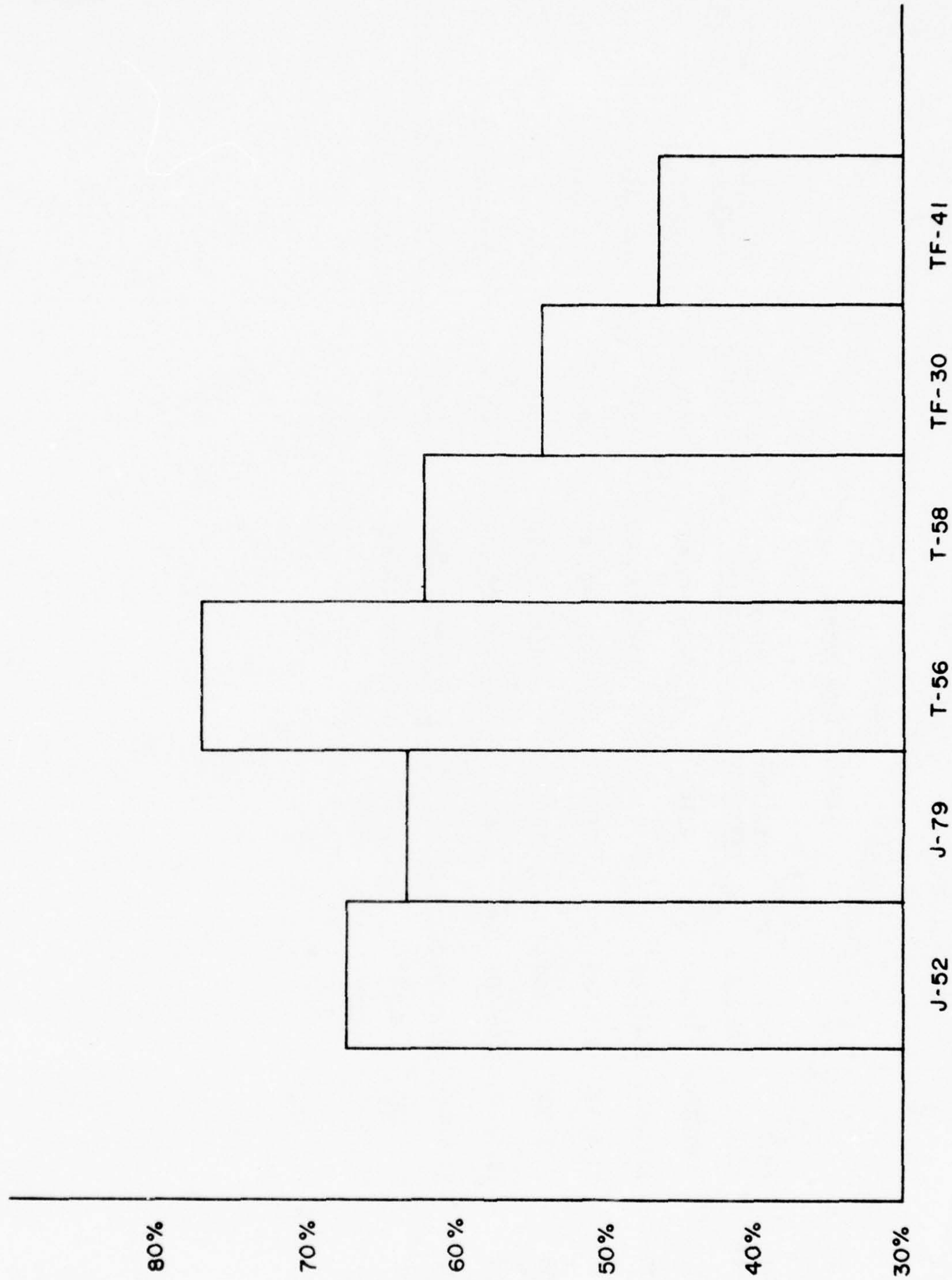
7. In view of the potential capability of a non-integrated diagnostic system to reduce maintenance costs, improve flight safety and enhance operational readiness, it is concluded that continued development of the proposed system is economically justified.

TABLE XI

ENGINE DATA MATRIX

MODEL ENGINE	UNIT COST	OVHL COST (1)	TOTAL NO. INVENTORY	INVENTORY VALUE ($)	TOTAL NO. INSTALLED	INSTALLED VALUE ($)	OPERATING/ VALUE RATIO
J-52	$202,400	$20,240	2116	$428,278,400	1424	$288,217,600	67.3%
J-79	$275,000	$27,500	2104	$578,600,000	1331	$366,025,000	63.3%
T-56	$126,500	$12,650	7524	$951,786,000	5809	$734,838,500	77.2%
T-58	$ 71,500	$ 7,150	2318	$165,737,000	1445	$103,317,500	62.3%
TF-30	$825,000	$82,500	873	$720,225,000	476	$392,700,000	54.5%
TF-41	$224,400	$22,440	442	$ 99,184,800	207	$ 46,450,800	46.8%
TOTAL	$287,466 (AVG)	$28,747 (AVG)	15,377	$2,943,811,200	10,692	$1,931,549,400	

(1) 10% of unit cost



OPERATING / VALUE RATIOS
FIGURE 5

H. INITIAL DIAGNOSTIC SYSTEM.

1. Included Equipment/Techniques. Fault detection and isolation of the four most prevalent aircraft gas turbine engine malfunctions, as identified in report NAEC-GSED-85, is proposed to be accomplished by utilization of the equipment/techniques at the indicated level of maintenance as summarized in Table XII. The engine is assumed to be installed in-aircraft at the "O" level and uninstalled at the "I" and "D" levels. The extent of diagnosis is not necessarily identical at each maintenance level.

2. Excluded Elements/Methods. The following elements were considered for possible inclusion in the non-integrated gas turbine engine diagnostic system but have been judged to have insufficient potential, effectiveness or applicability to warrant either continued usage or further development.

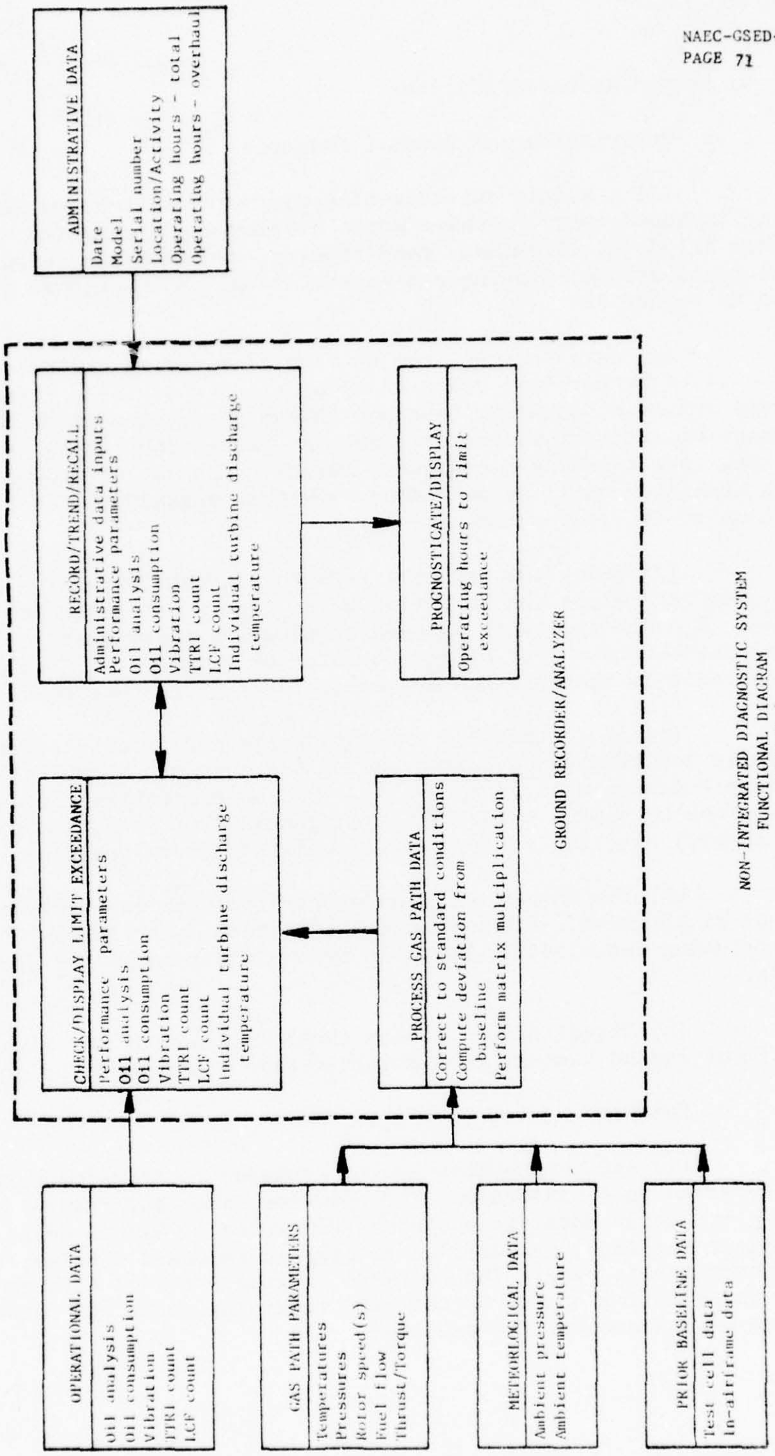
Sonic Analysis
Holography
Radioactive Temperature Indicator
Optical Pyrometer
Thermogram
Thrust Computing System
T-56 Engine Performance and Trend Analysis Program
GS7800 Fuel Control Performance Analyzer
Laser Vibration Sensor
Shock Pulse Meter
Electrostatic Probe

3. Functional Relationship Between Diagnostic Elements. The functional relation of elements amenable to numerical evaluation which comprise the proposed non-integrated system is presented in Fig. 6. Automatic data processing, contingent upon successful implementation of gas path analysis, is proposed by the method described in Paragraph 4. Specific details and parameters to be recorded are unique for a particular model engine however, equipment flexibility should allow adaptation to all engines. Provisions are to be included for both manual and automatic data entry to best accomodate quantities not practically adaptable to automatic entry but nevertheless to maintain a complete record at a single location. It is envisioned that a magnetic tape data record, with complete engine history, will accompany the engine similar to the conventional log book.

TABLE XII

SUMMARY OF DIAGNOSTIC ELEMENT UTILIZATION

MALFUNCTION	NON-INTEGRATED ELEMENT	MAINTENANCE LEVEL		
		O	I	D
FOREIGN OBJECT DAMAGE	BORESCOPE	X	X	X
	GAS PATH ANALYSIS EQUIPMENT	X	X	
HOT SECTION DISTRESS	BORESCOPE	X	X	X
	GAS PATH ANALYSIS EQUIPMENT	X	X	
	TTRI/LCF COUNTER	X		
	TURBINE DISCHARGE TEMP. (INDIVIDUAL TREND)	X	X	
INTERNAL OIL LEAKAGE	OIL CONSUMPTION (TRENDED)	X	X	
EXCESSIVE VIBRATION	VIBRATION SIGNAL ANALYSIS EQUIPMENT	X	X	X
	VIBRATION TESTERS	X		
	TEST SYSTEM VIBRATION EQUIPMENT		X	X
OTHER MALFUNCTIONS	TEMPERATURE SENSING SYSTEM TESTER	X	X	X
	OIL ANALYSIS EQUIPMENT	X	X	X
	JETCAL ANALYZER	X	X	X
	TRIM TESTERS	X		



NON-INTEGRATED DIAGNOSTIC SYSTEM
FUNCTIONAL DIAGRAM
FIGURE 6

4. Ground Recorder/Analyzer.

a. Description and Special Features.

(1) A single suitcase-size microprocessor-based instrument having keyboard entry, alpha-numeric display and a cassette drive will perform all data collection, conditioning, and compression as well as trend calculations, logging and presentation. A functional diagram is shown in Figure 7.

(2) Data sampled from on-line transducers and sensors and that entered by keyboard are used to update the engine's permanent history stored on magnetic tape and extend the time plot of each performance or interest parameter. Further processing, using regression and long-term trending techniques, yields a display of the operating hours remaining until an exceedance limit is reached for each performance or interest parameter.

(3) Using the magnetic tape log, a more extensive analysis of unique parameters can be performed at the intermediate and depot levels. A connector cable is used to plug the instrument into the serial asynchronous port of any computer or terminal. Quick data transference is accomplished by initiating a paper tape read command.

(4) As testing and evaluation proceed, modifications can be easily implemented by reprogramming the software algorithms; no hardware redesign will be necessary. One instrument can be used for all engines by simply changing the pluggable PROM (programmable, read only memory) used for storing an engine's signature constants.

(5) The number of transducers processed can vary with engine type or be expanded. A bus-oriented structure makes further expansion of processing capabilities possible by the addition of the necessary boards.

(6) Direct memory access (DMA) is used for the simultaneous read-in of engine history from magnetic tape and transducer sampling.

b. Hardware.

(1) All components, except transducers and wire harnesses, are contained in a briefcase. The operator makes entries to control testing and input data via a hand-held terminal. Sample means of the transducer readings, in addition to certain keyboard entries, are logged onto magnetic tape. The operator is also provided with an estimate, in operating hours, of the time remaining until the performance or interest parameters are exceeded.

(2) Magnetic Tape Unit-Program and historical data loading, update logging, and computer-to-computer data transfer are all accomplished by a cassette drive which can read and write at speeds up to 1,200 bits per second and can be plugged into the serial asynchronous port of any computer or terminal. A standard cassette containing 282 feet of tape and using 800 bpi packing should hold at least three years of diagnostic engine data. Calibration and test routines can also be stored on cassettes if an interpreter for translation is added later.

(3) Terminal - Control, data entries and display are all performed on a hand-held device attached by cable to the primary unit. This mini-terminal has a twenty key pad, shift buttons and a dot matrix display. All control, special and alphabetical characters and numerals can be generated and presented.

(4) Microprocessor System - Microprocessors can perform logical decisions and computations quickly and cheaply. They are easily modified and reprogrammed. They are also small and have modest power requirements. An instrument built around these attributes can be powerful yet very portable, relatively inexpensive, flexible, expandable and can be improved readily as new technologies arise.

(5) All diagnostic processing will be performed by an 8-bit microprocessor using 7-bit ASCII code for interfacing; sample data will reside in 32 kilobits of RAM (random access memory). Program and influence coefficients will be permanently stored in PROM's.

(6) For efficient transfer, data will be collected into 16-bit words. Large scale integration (LSI) technology will be used for analog-to-digital conversion, formatting, multiplexing, etc., as well as in processor and memories.

c. Input. Initially, the engine's administrative data and operating hours are entered manually and verified. A check for stabilized engine conditions is made. Then each transducer is polled, its output standardized, digitized and stored. Simultaneously, the historical record on magnetic tape is read into memory. Lastly, oil analysis results and usage, vibration, TTRI count and LCF count are entered via the keyboard.

d. Pre-Processing.

(1) Perform validation and stablization checks on all incoming data.

(2) Poll transducers until a good sample of each measured parameter is obtained.

(3) Digitize and format each parameter.

(4) Adjust each to standard day operating conditions.

e. Processing.

(1) Determine the sample mean of each measured parameter.

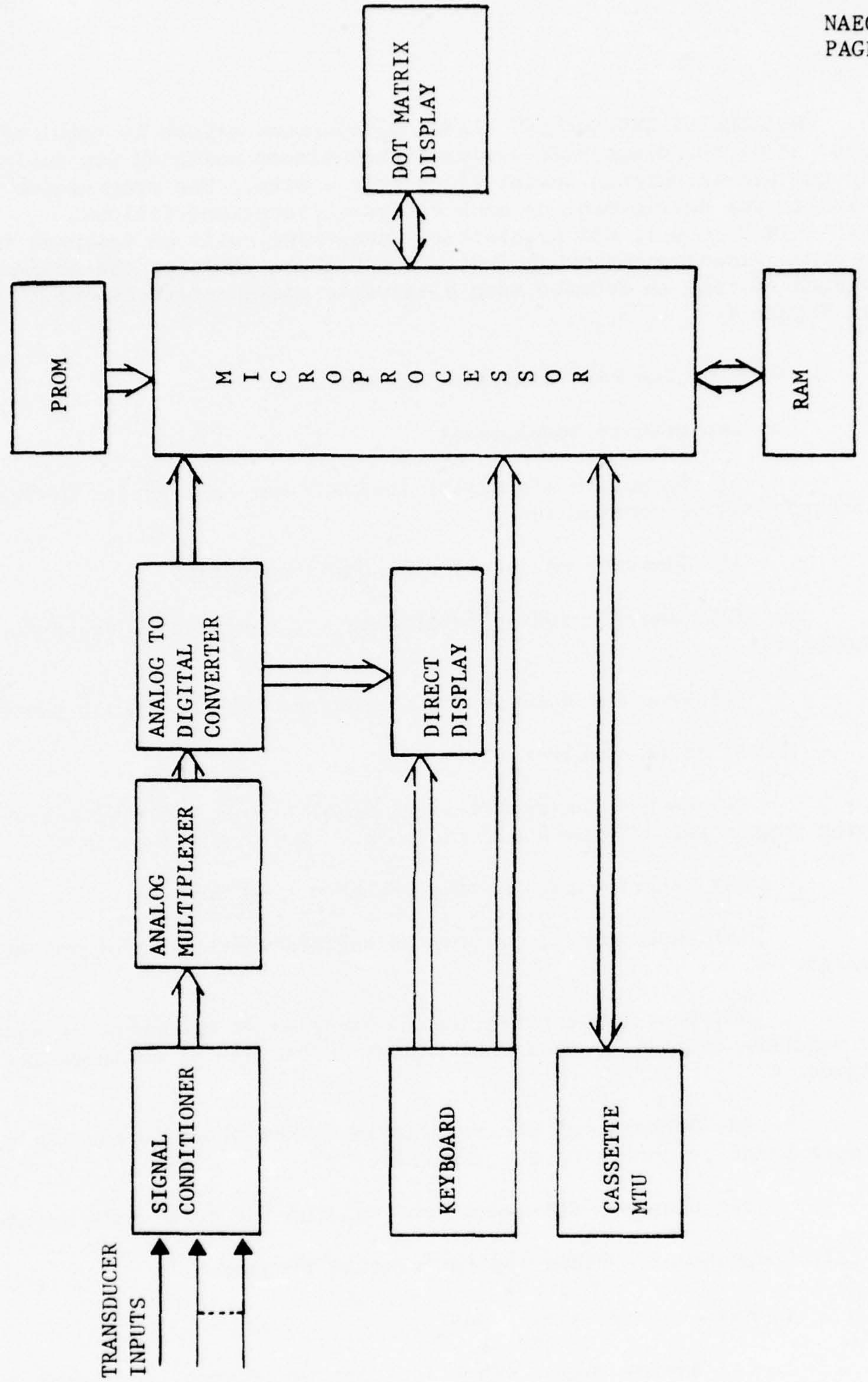
(2) Compare each mean with the ROM-stored baseline peculair to the engine type and determine the differential factor ($\Delta V/V$).

(3) Construct a column matrix of these differential factors. Multiply it and the influence coefficient matrix to obtain a column matrix of performance parameters.

(4) Put performance parameters on magnetic tape for update of historical record.

(5) Using past performance parameters, now in RAM, and those just determined, construct a time plot.

(6) Apply smoothing, multiple regression and extrapolation techniques to determine the number of hours remaining until the limit exceedance of that particular parameter is reached. (Non-baseline dependent parameters, such as turbine out temperatures, oil analysis and usage are immediately compared with past values and trended.



GROUND RECORDER/ANALYZER

FUNCTIONAL DIAGRAM

FIGURE 7

I. ENGINEERING DEVELOPMENT PLAN. Development effort is required on several of the diagnostic equipment/techniques selected for inclusion in the non-integrated engine diagnostic system. The progressive evolution in the development of each equipment/technique follows. NAVAIRINST 5000.1, GSE Acquisition Management, will be followed for program planning and management. A milestone chart of the estimated length of time to develop each diagnostic equipment/technique is shown in Figure 8.

1. Develop Gas Path Analysis Equipment.

a. Exploratory Development.

(1) Formulate a gas path analysis methodology for several aircraft/engine combinations.

(2) Generate necessary diagnostic equations.

(3) Generate design parameters for envisioned Ground Recorder/ Analyzer.

(4) Generate documentation required for conceptual phase.

b. Advanced Development.

(1) Develop an experimental model Ground Recorder/Analyzer using commercial off-the-shelf equipment. Reference Section H.

(2) Experimental testing of known good engines.

(3) Experimental testing of engines with known or suspected faults.

(4) Experimental testing in-airframe at an operating squadron to validate capability to detect incipient failure of an installed engine.

(5) Retrofit of aircraft/engine combination to provide a single-point connector on the aircraft.

(6) Generate documentation required for full-scale development.

2. Comprehensive Vibration Correlation Program.

a. Exploratory Development.

(1) Review engine vibration test procedures, equipment and requirements.

(2) Complete correlation testing with A-7E/TF-41 and H-46/T58.

(3) Establish degree of correlation between in-airframe and in-test system data.

(4) Identify areas/degree of advanced development and testing.

(5) Generate documentation required for conceptual phase.

b. Advanced Development.

(1) Develop experimental model vibration test equipment.

(2) Continue correlation testing.

(3) Generate documentation required for full-scale development.

3. Oil Analysis Methodology Development.

a. Exploratory Development.

(1) Develop sampling technique.

(2) Verify sampling techniques by field testing.

(3) Develop particulate analysis technique.

(4) Verify particulate analysis technique by field testing.

(5) Develop analysis criteria.

(6) Generate documentation required for full-scale development.

4. Temperature Sensing System Tester.

a. Full-Scale Development.

(1) Generate documentation necessary for full-scale development phase.

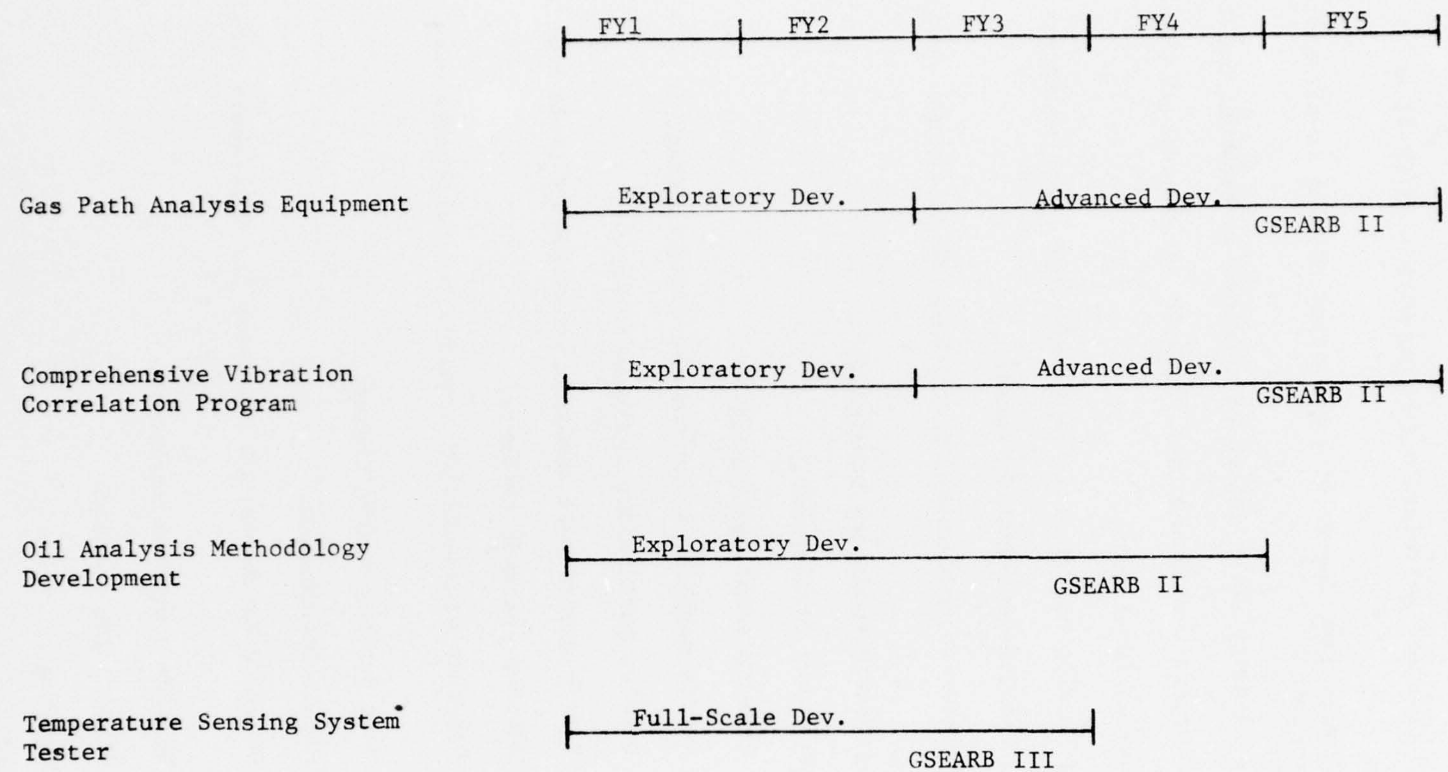
(2) Develop prototype equipment.

(3) Development testing.

(4) Techeval.

(5) ASU (Approval for Service Use)

(6) Generate documentation necessary for production phase.



NON-INTEGRATED DIAGNOSTIC SYSTEM

MILESTONE CHART

FIGURE 8

VII. CONCLUSIONS

1. A non-integrated gas turbine engine diagnostic system is achievable through the use of several complementary diagnostic elements as summarized in Table XII.

2. Continued use of existing diagnostic elements (e.g., trim testers and Jetcal Analyzers) will be required for some existing aircraft/engine combinations. In these cases, it is not economically feasible to accomplish retrofit of the aircraft engine and test set adapter cables to utilize newer design equipment/techniques.

3. Development effort, including extensive experimental testing, is required on several of the diagnostic elements comprising the non-integrated system.

4. The Ground Recorder/Analyzer developed under a gas path analysis program would provide a central location for recording and trending of all available condition monitoring data on an engine serial number basis. It would also incorporate the engine trim function.

5. There is no need in the near future for development of additional trim testers except that a new design TF41 Temperature Limiter Amplifier Test Set is needed.

6. Existing Jetcal Analyzers are a high maintenance and operating cost item. A new Aircraft Engine Temperature System Tester would eliminate this equipment and provide O-level capability for static check of thermocouple systems which have integral harnesses or have inaccessible thermocouple probes.

7. Gas path analysis, with trending, and borescope inspection are the most effective methods for diagnosing FOD and hot section distress.

8. Borescopes in Navy inventory satisfactorily meet the requirements for borescope inspection except for the Lenox Universal Fiber Optic Borescope, Model AE36D-2.

9. Effective use of the borescope is reduced, in some cases, by lack of training in borescope operation and interpretation.

10. Trending oil consumption, using the Ground Recorder/Analyzer, would detect excessive oil leakage but would not provide fault isolation.

11. Meaningful hot section temperature counter and low cycle fatigue counter data, when available, would be a valuable input to the Ground Recorder/Analyzer for diagnosis of hot section distress.

12. Oil analysis techniques being developed by NAVAIRENGCEN indicate vastly increased potential to detect incipient failure of bearings and other oil-wetted components as compared to spectrometric analysis.

13. Whether vibration limits specified in existing test system and airframe maintenance manuals are meaningful is questionable. Correlation between go-no go limits in-fixed test system, in-portable test system and in-airframe are not established.

14. Current signal analysis equipment/techniques at "O", "I" and "D" levels are inadequate for fault isolation in a no-go situation.

15. A small engine-mounted FOD detector utilizing a bearing-mounted accelerometer is one of the promising techniques to record the occurrence of and magnitude of a FOD strike.

VII. CONCLUSIONS

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15. A small engine-mounted FOD detector utilizing a bearing-mounted accelerometer is one of the promising techniques to record the occurrence of and magnitude of a FOD strike.

VIII. RECOMMENDATIONS

1. Develop a gas path analysis technique for engine condition monitoring including a flight line Ground Recorder/Analyzer.

2. Initiate a comprehensive gas turbine engine vibration correlation program.

3. Continue the NAVAIRENGCEN Oil Analysis Methodology Development Program to develop an effective oil analysis equipment/technique.

4. Where economically justifiable, continue to replace "unique" trim testers and Jetcal Analyzers with the A/E24M-28 and TTU-347/E Trim Testers.

5. Continue the development of a new TF41 Temperature Limiter Amplifier Test Set.

6. Develop an Aircraft Engine Temperature System Tester to eliminate the Jetcal Analyzer and provide O-level capability for static check of thermocouple systems and integral harnesses and inaccessible thermocouple probes.

7. Continue NAVAIRENGCEN efforts to provide adequate borescopes to the fleet. Replace the Lenox Universal Fiber Optic Borescope, Model AE36D-2 where economically justifiable.

8. Training in borescope operation and interpretation should be considered.

9. Assure adequate accessibility for borescope inspection in future design engines.

10. Oil consumption should be trended using the Data Recorder/Analyzer to prognose operating hours to limit exceedance.

11. Input hot section temperature counter and low cycle fatigue counter data, when available, to the Ground Recorder/Analyzer for diagnosis of hot section distress.

12. The development of an effective, light-weight, engine-mounted FOD detector, utilizing a bearing-mounted accelerometer, should be considered for installation in future design engines.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Diagnostic equipment and techniques to be included in a non-integrated system to detect and isolate the four most prevalent malfunctions in Navy aircraft gas turbine engines were selected. Each of twenty-five candidate elements were considered on the basis of technical feasibility, cost-effectiveness, and diagnostic need.

Gas path analysis, with trending, and borescope inspection were selected as the most effective methods to diagnose the leading engine malfunctions (63%),

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foreign object damage and hot section distress. Other elements to be included in the proposed embryonic system are oil analysis, time temperature recording indicator/low cycle fatigue counters, vibration testers, trim testers, test system vibration equipment, vibration signal analysis equipment, temperature sensing system tester, and Jetcal Analyzer. Oil analysis techniques being developed indicate a significant improvement compared to spectrometric analysis for diagnostic purposes. A summary of specific elements for utilization at each of three levels of maintenance and an engineering development plan with proposed implementation milestones are included.

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